Words to communicate concepts

Brookhaven National Laboratory **Relativistic Heavy Ion Collider**

Understanding
Observation
Experiment
Theory
Light Wave
Photon

small, very small
very fast
Mechanics:
Classical
Quantum
Relativistic

Leptons

Electron e^- Positron e^+
Muon μ^- μ^+ Tau τ^- τ^+
Neutrinos ν_e ν_μ ν_τ

The Atom
Hard Sphere Model
Plum Pudding Model
Nuclear Atom
Soft/Hard Scattering
Electron Wave
Wave-Particle Duality
Quantum Mechanics

The Nucleus
Nucleons:
Proton & Neutron
Radioactive Decay

Particles & Fields
Parton: Quarks
and Gluons
Baryons, Hadrons
π Meson (pion)

Strong suppression
Dense final state
Anisotropic Flow
Nearly perfect fluid
Asymptotic Freedom
Phase Transitions
Deconfinement
Early Universe
(Big Bang)

Direct and Virtual Photons
Hottest Temp. Measured

Modern Physics:
Understanding the very small and the very fast

Brant M. Johnson

- **Atomic, Nuclear, and Particle Physicist**
- **Plasma, Beams, and Atomic Physics Editor**
- **Publications Coordinator for PHENIX Collaboration**
- **Chair, Physics Department ESSH Committee**
- **Former-Chair, RHIC & AGS Users' Executive Com.**
- **Former-Chair, National User Facility Organization**
- **Outreach and Educational Program Speaker**
- **Helping to develop K-12 common core standards**

ACHIEVE: http://www.achieve.org/achievingcommoncore

The National Governors Association (NGA) and Council of Chief State School Officers (CCSSO) are committed to a state-led process –- the Common Core State Standards Initiative (CCSSI)

Goal: ***All students should graduate from high school prepared for the demands of postsecondary education, meaningful careers, and effective citizenship.***

English and Language Arts, Mathematics, and Literacy in History/Social Studies, Science, and Technical Subjects.

Experts understand the core principles and theoretical frameworks of their field.

Their retention of detailed information is aided by an understanding of its placement in the context of these principles and theories.

Learning to understand science or engineering in a more expert fashion requires development of an understanding of how facts are related to each other and to overarching core ideas.

Physics Week (continued)

Tuesday

Milind Diwan -- Physics at BNL

Christoph Montag -- Relativistic Heavy Ion Collider (RHIC) Tunnel Tour

Gene van Buren -- STAR Detector Tour

Paul Sorenson -- Physics Colloquium “Sambamurti Lecture”

Wednesday

Marc- Andre Pleier -- Large Hadron Collider (LHC) and the Atlas Detector

Peter Wanderer -- Magnet Factory tour

NOAA at BNL -- Doppler Radar/Weather Balloon Launch

Thursday

William Sherman -- Center for Functional Nanomaterials (CFN)

Stefan Tafrov and Michael Sivertz -- NASA Space Radiation Lab (NSRL)

Friday

Hakeem Oluseyi -- Near-Field Cosmology

Cecilia Hanke-Sanchez -- Physics of National Synchrotron Light Source

Learning (Memorizing) vs Understanding (Knowing)

A child can learn or memorize that:

1 + 1 = 2 or 2 - 1 - 1 = 0

but 1, 2, and "zero" are abstract concepts.

For a child: **Understanding comes from experience. Give a child one toy and then another. The child understands having fun playing with one + one equals two toys.**

Subtraction: Take the two toys away abruptly: Now the child now knows what "zero" means and may even cry based on true understanding.

Usual Definition:

Physics is the Study of Matter

Ancient Meaning:

Physics is from the Greek word PHYSIS, which means:

The attempt to “see” the nature of things

Small → smaller → smaller → smallest?

People →

Organs →

Cells →

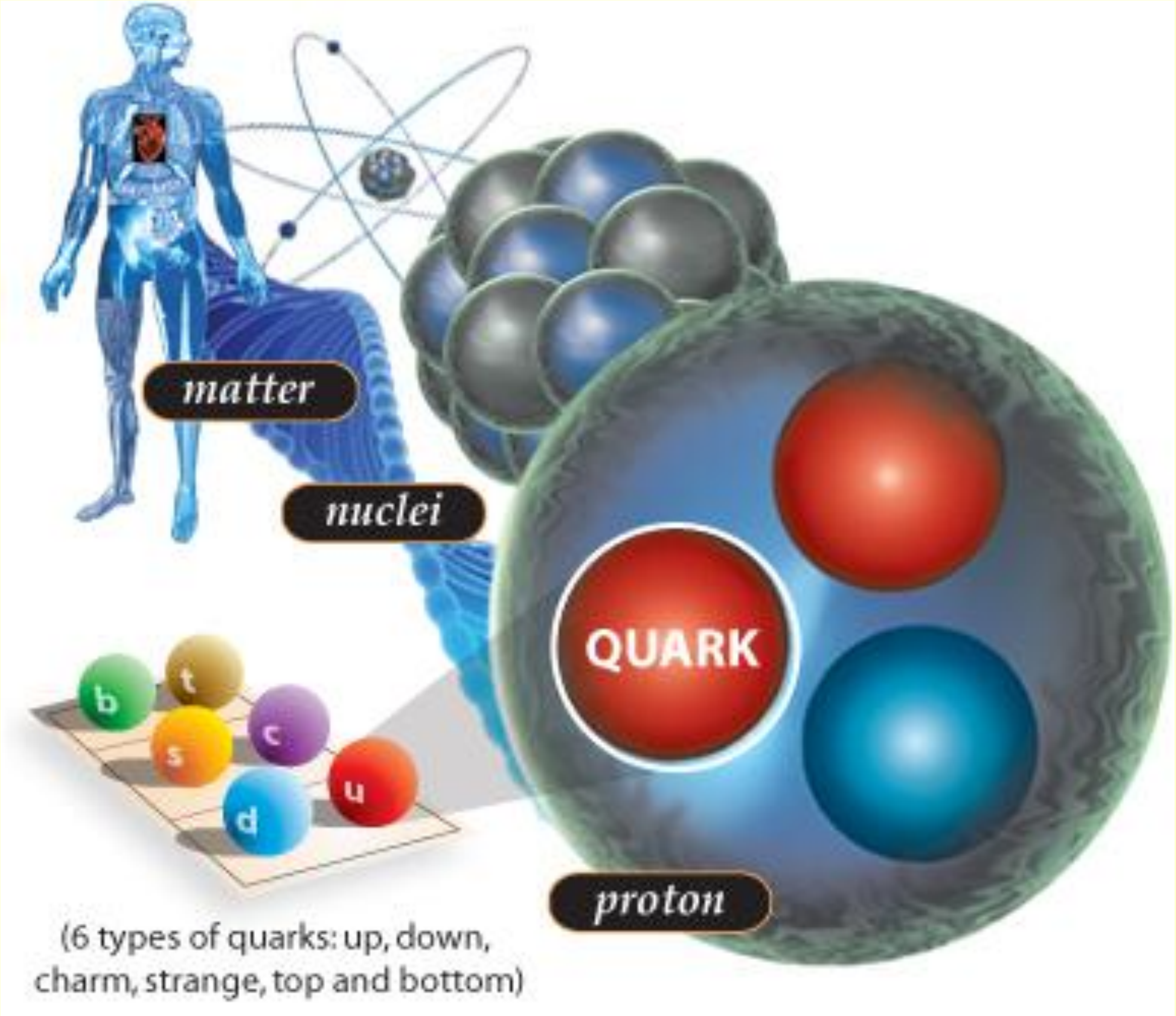
Molecules →

Atoms →

Electrons
and nuclei →

Protons
and neutrons →

Quarks and gluons →



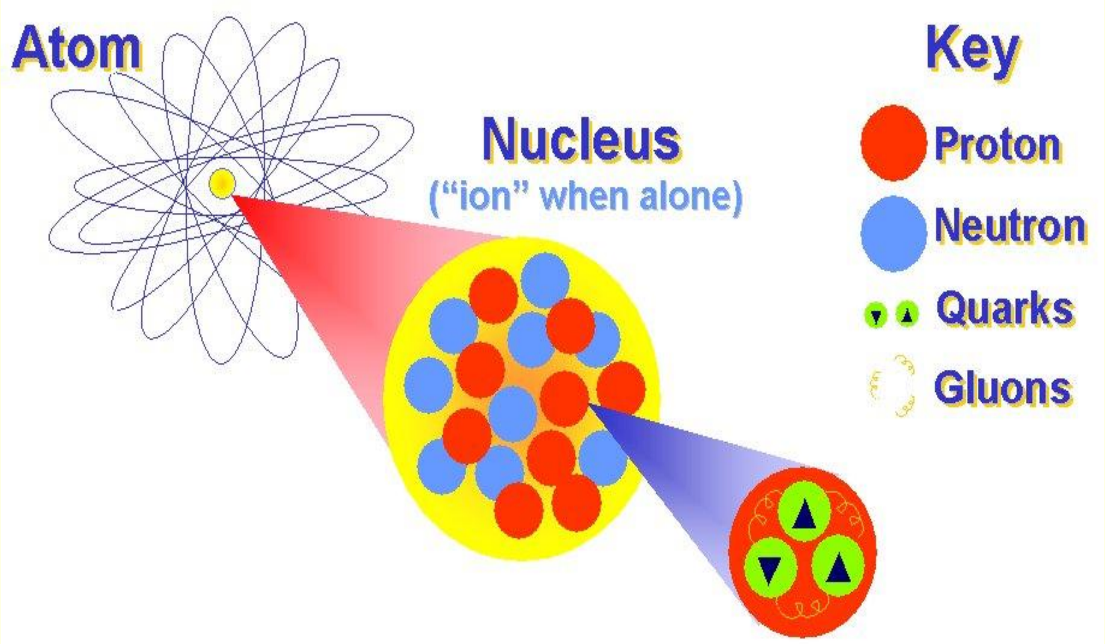
A ... sense ... of ... Wonder

Small,

→ → →

smaller,

→ → →



even smaller,

→ → →

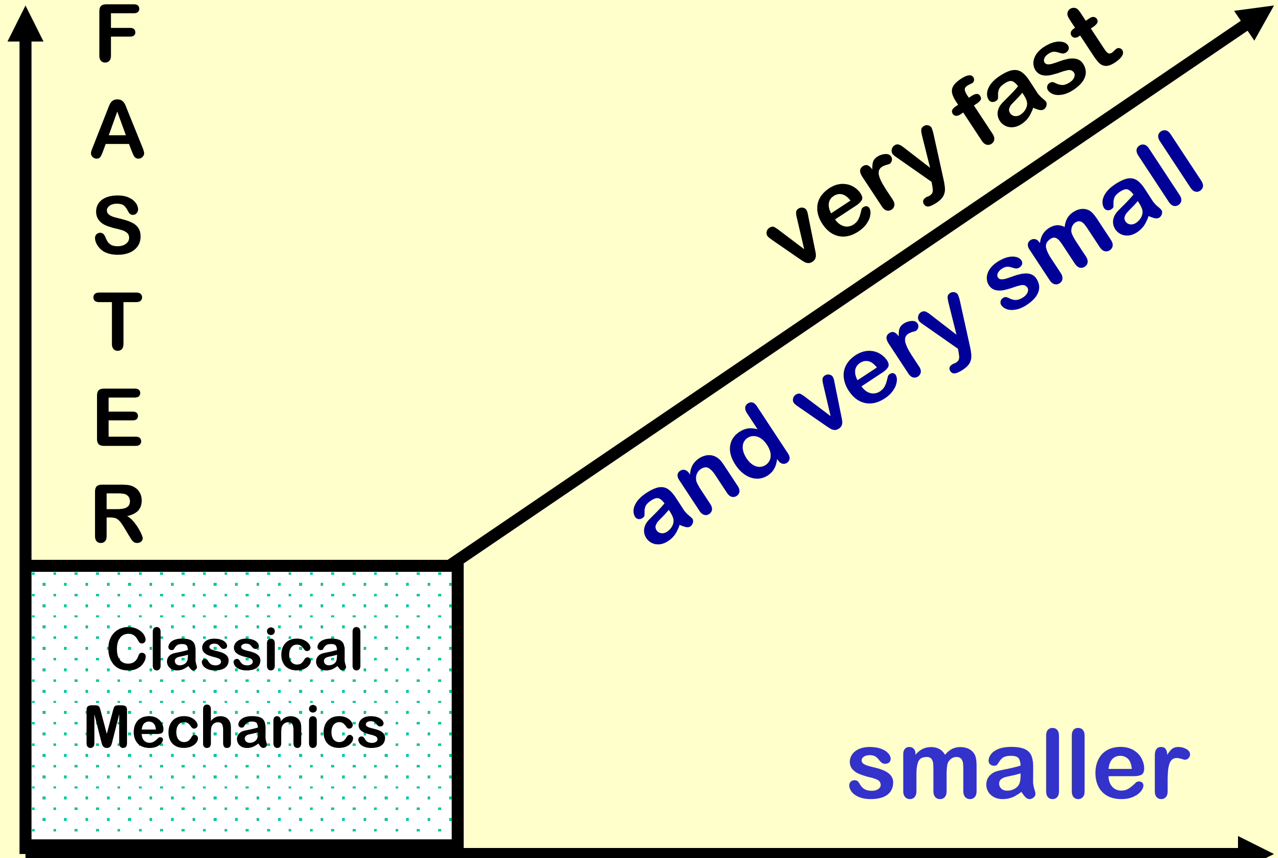
and smaller

→ → →

smallest?

The Very Fast and the Very Small

Peta	10^{15}	PeV
Tera	10^{12}	TeV
Giga	10^{9}	GeV
Mega	10^{6}	MeV
Kilo	10^{3}	keV
1	10^{0}	eV

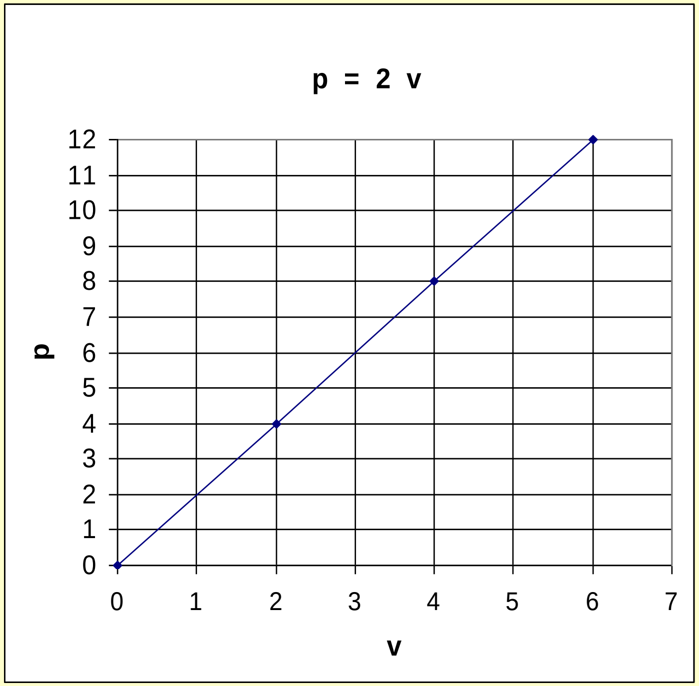


1.E+00	1.E-03	1.E-06	1.E-09	1.E-12	1.E-15	1.E-18
meter	m	ц	n	p	f	a
1	milli	micro	nano	pico	femto	atto

In Classical Physics (the large and the slow):
linear momentum (p) equals mass (m) times velocity (v)

$p = mv$ (linear equation: $y = a\,x$)

Visualize example,
If $m = 2$, then $p = 2\,v$



Ah, but how can we truly UNDERSTAND momentum?

Force is change in momentum w.r.t. time.

$$F = dp / dt$$

If I offer to toss to you either a tennis ball or a bowling ball at the same velocity, which one would you be willing to catch?

Understanding Classical Energy

In Classical Physics (the large and the slow), Potential Energy is mass (m) times gravitational const, (g) times height (h):

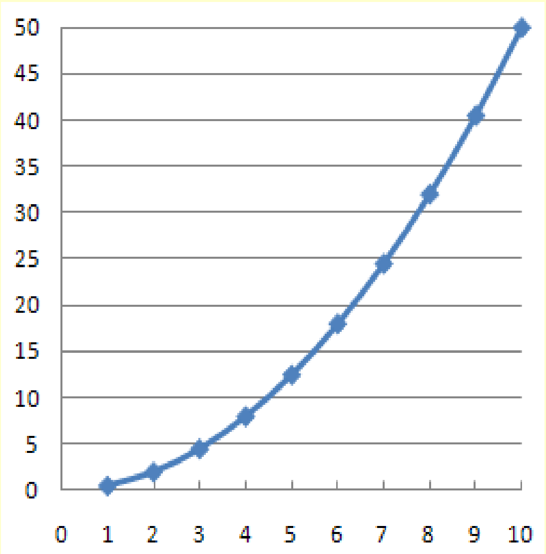
$$P.E. = mgh$$

Kinetic Energy is ½ mass (m) times velocity (v):

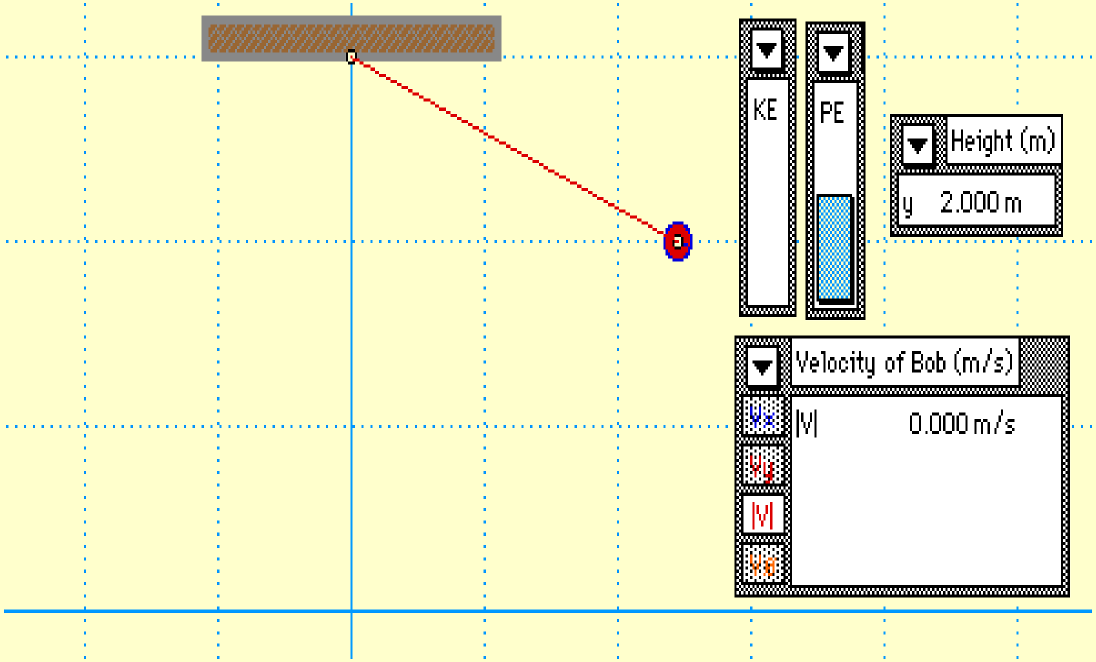
$$K.E. = \tfrac{1}{2} m v^2$$

Total Energy (Etotal) is the sum: $P.E. + K.E. = E_{total}$

K.E.

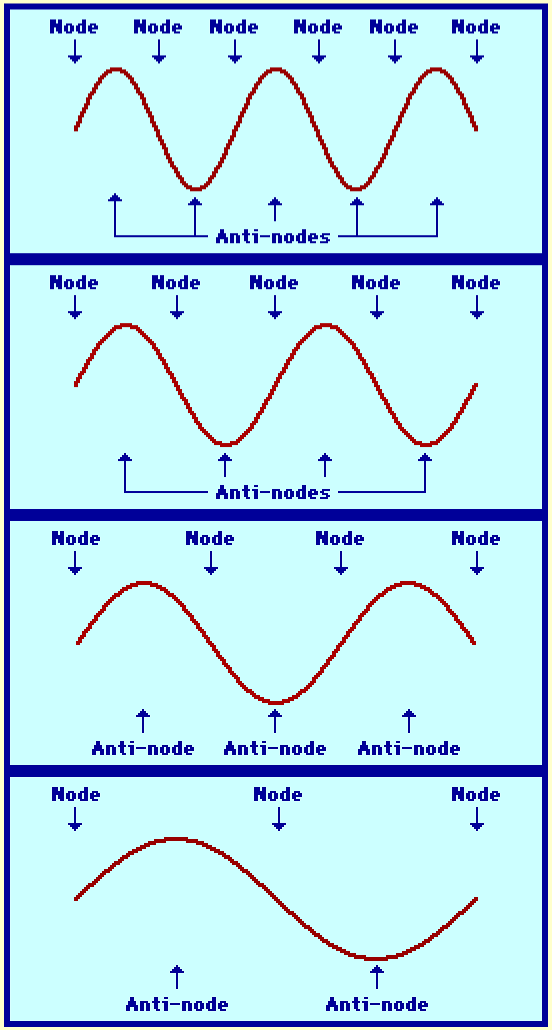


V



Understanding Waves

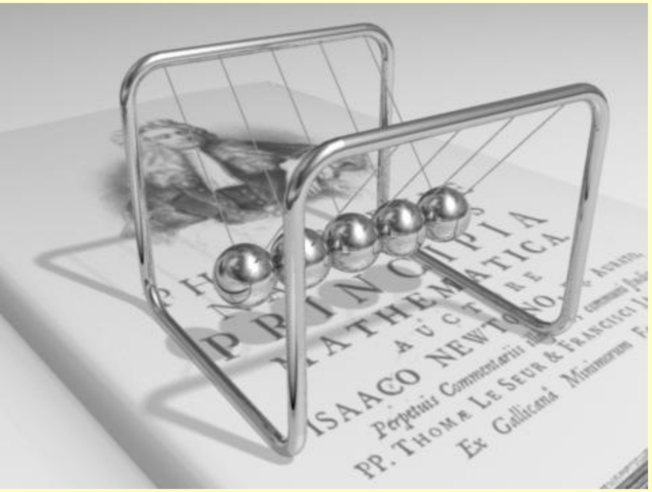
$(1/\lambda \propto \nu \propto E)$

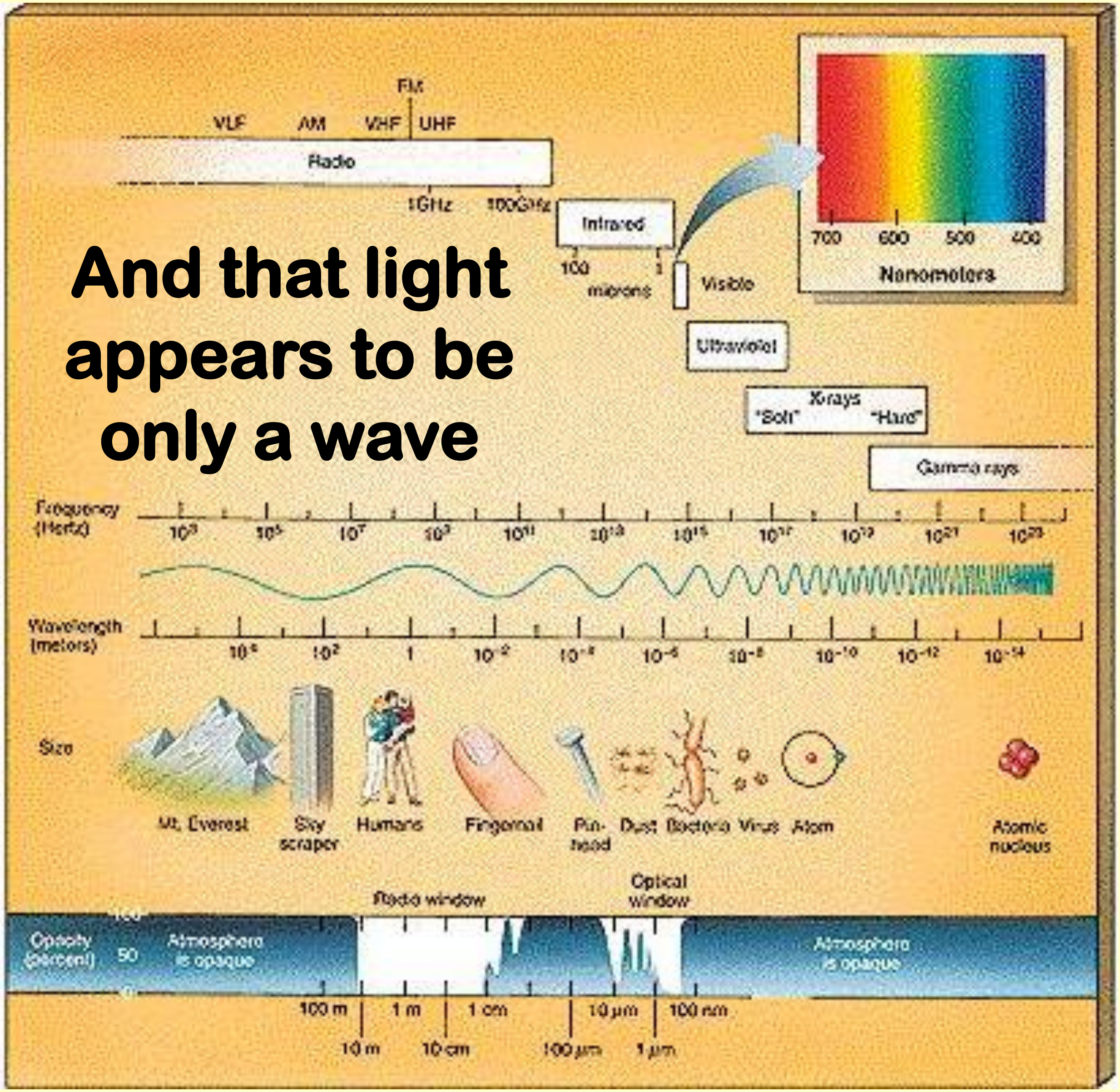


λ wavelength	ν frequency	E Energy
$2/5\ \lambda_0$	$5/2\ \nu_0$	$5/2\ E_0$
$1/2\ \lambda_0$	$2\ \nu_0$	$2\ E_0$
$2/3\ \lambda_0$	$3/2\ \nu_0$	$3/2\ E_0$
λ_0	ν_0	E_0

Conservation of Energy and Momentum – Light

We observe in nature that for "particles" in motion energy and momentum are conserved

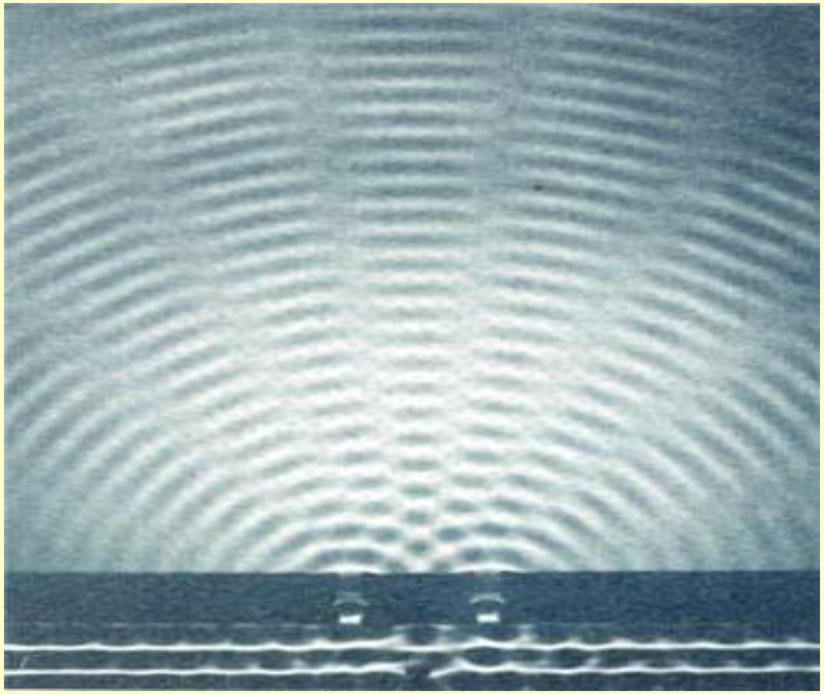


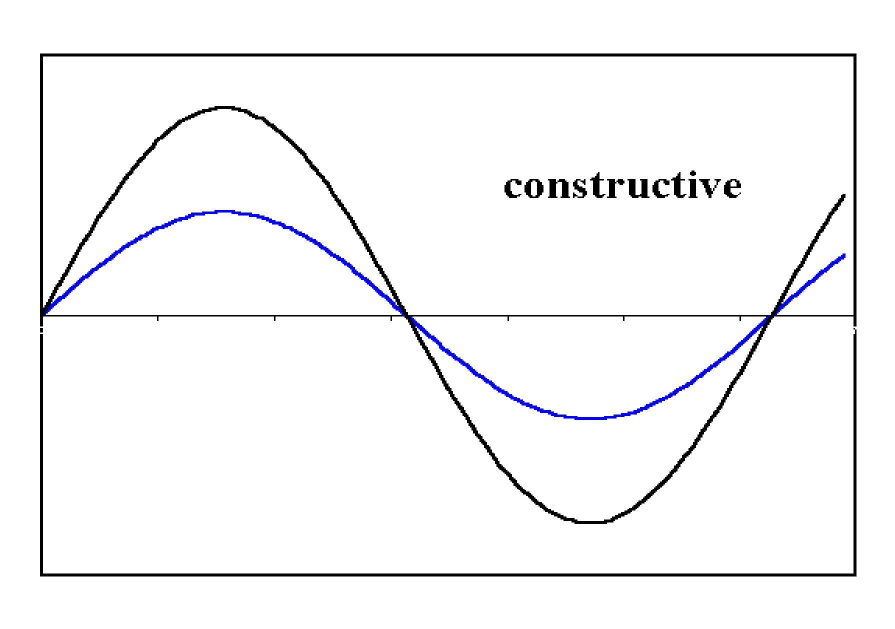


And that light appears to be only a wave

Waves and Diffraction

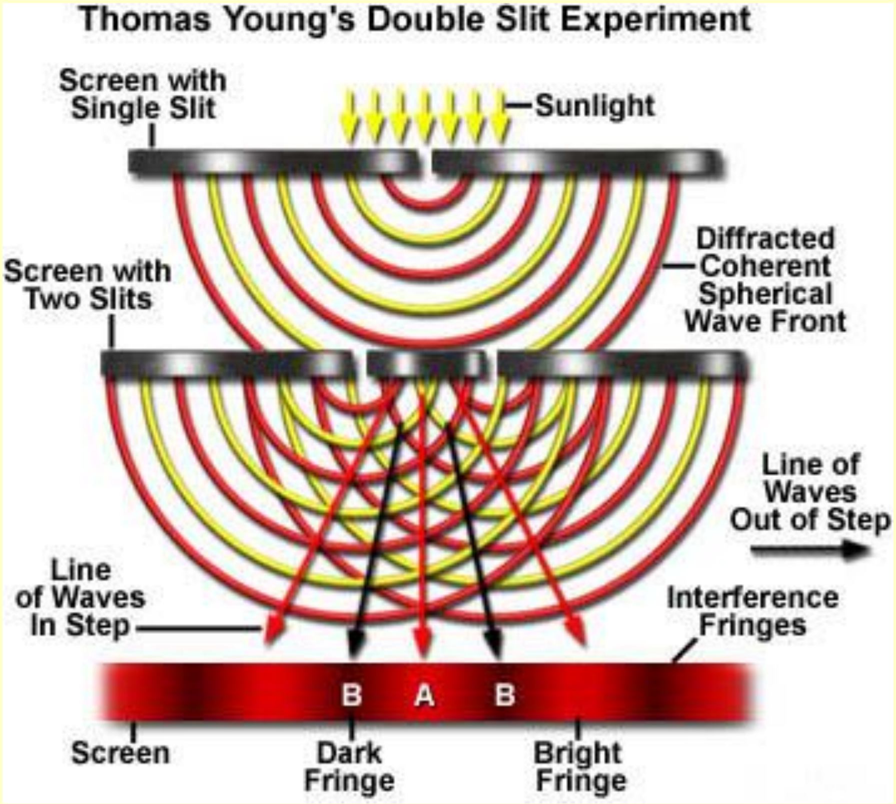
A wave moving through a single slit produces a circular wave pattern caused by <u>diffraction</u>. (pebble dropped in a pond).

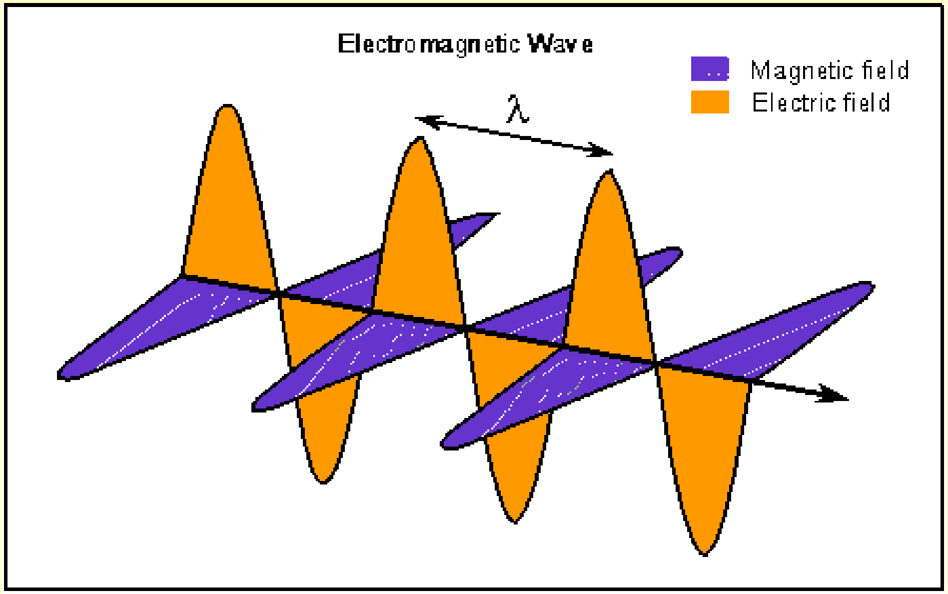




Waves passing through two slits cause constructive and destructive interference, producing a <u>diffraction pattern</u>.

Diffraction shows light is a wave

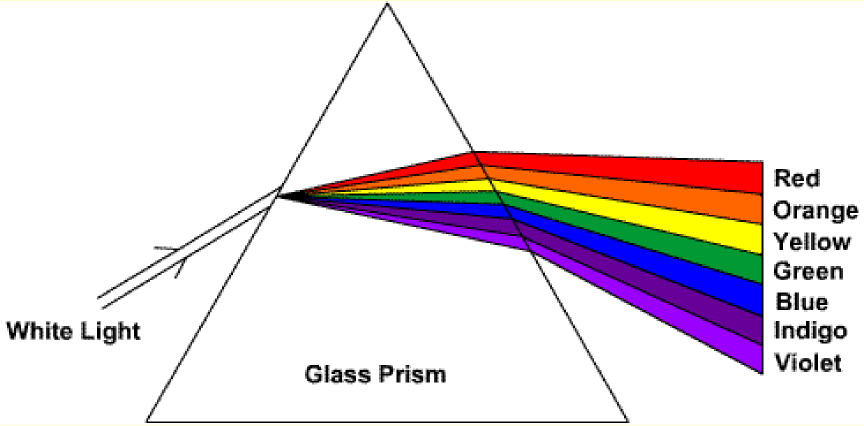


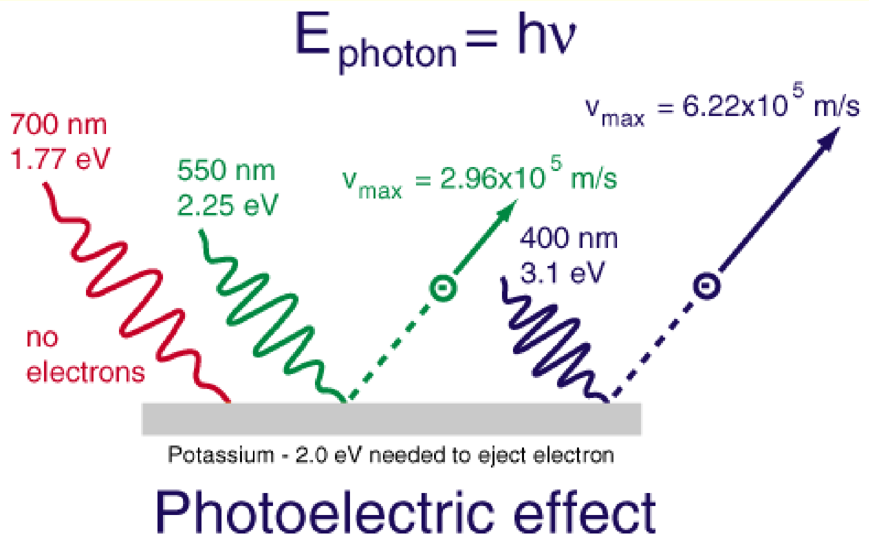


Young's Double-Slit Experiment in 1803 proved that light acts like a wave

But! It did not prove that light is only a wave.

Photons (particles of light or quanta)





1905 Albert Einstein

Explained the photoelectric effect using a mathematical description that assumed it was caused by absorption of quanta of light (now called photons).

Einstien showed how the "particles-of-light" concept explained the photoelectric effect in terms of absorption of discrete quanta.

Einstein's explanation of the photoelectric effect won him the Nobel Prize in Physics in 1921.

E_e(red)=0 E_e(green)=0.25 eV E_e(violet)=1.1eV

How do we advance our understanding of nature?

Aristotle **(384 – 322 BCE):** ***"Those who wish to succeed must ask the right preliminary questions."***

"Aristotle's Fundamental Propositions:

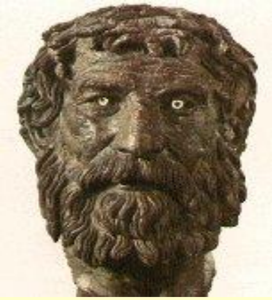
- **Logic is the essential method of all rational inquiry**
- **Theory should follow upon the empirical observation of nature and things.**

Yogi Berra: You can observe a lot by watching.

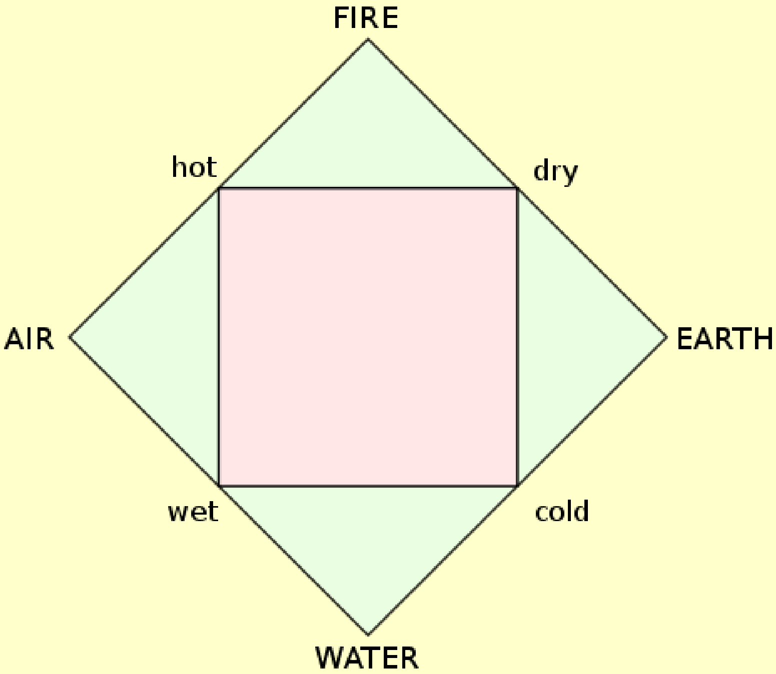
The test of all knowledge is experiment. EXPERIMENT is the SOLE JUDGE of SCIENTIFIC TRUTH. -- Richard P. Feynman

Asking a “right” preliminary question

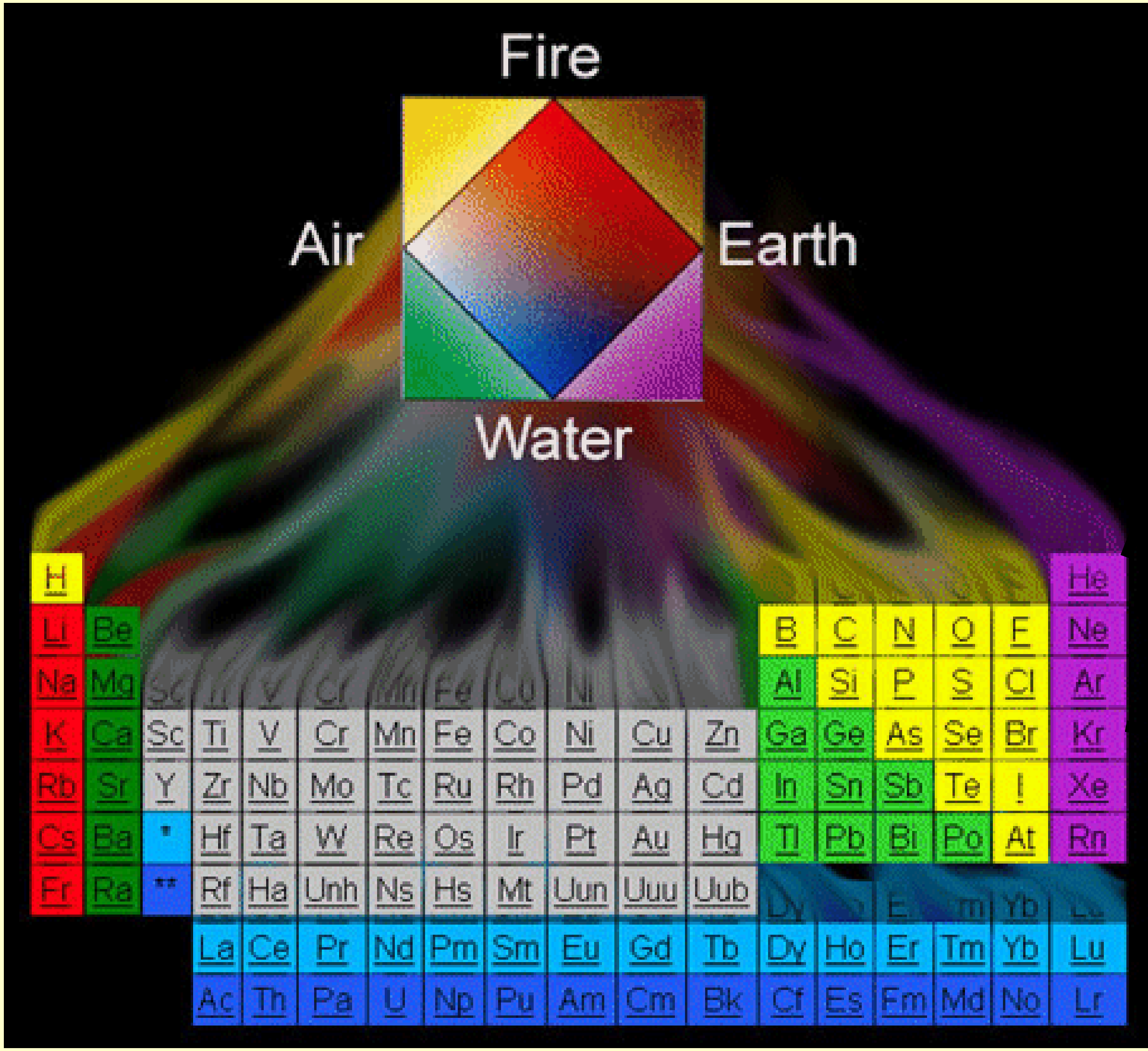
What are the Elements of Nature?

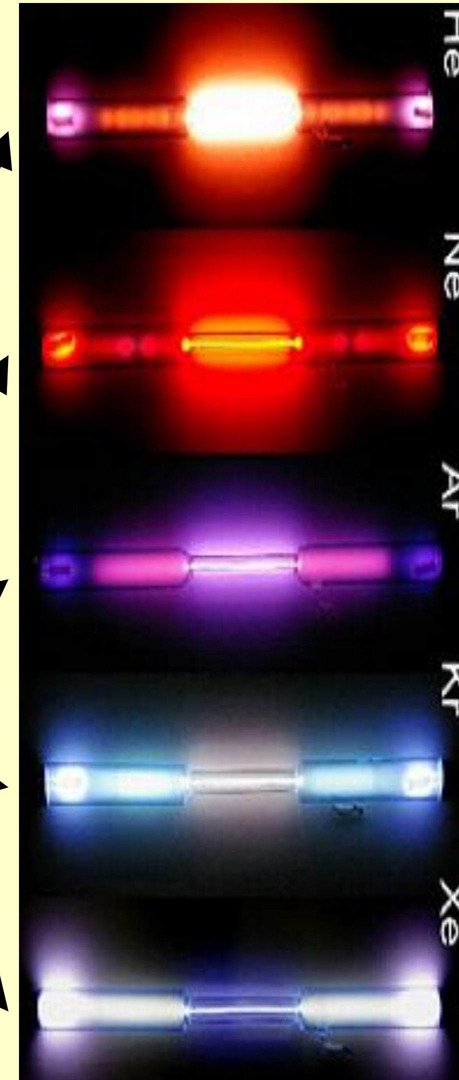


Empedocles (490-430 BCE) first classified the elements as fire, air, earth, water (Chinese added: wood, metal)



Periodic Table of the Elements





electrons (-1), protons (+1), neutrons (0)

Noble gases

What do we know about atoms?

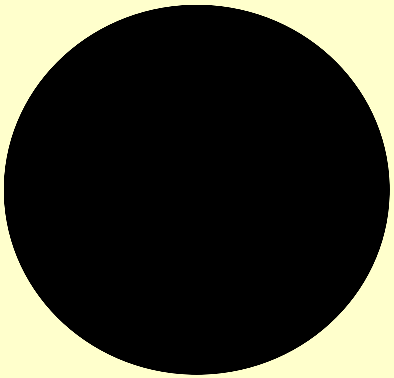
Things that we know today about

ATOMS

1. Very small: About 0.1nm across
2. Stable: Atoms can last forever
3. Electrically neutral (no net charge)
4. Emit and absorb light at discrete wavelengths and energies

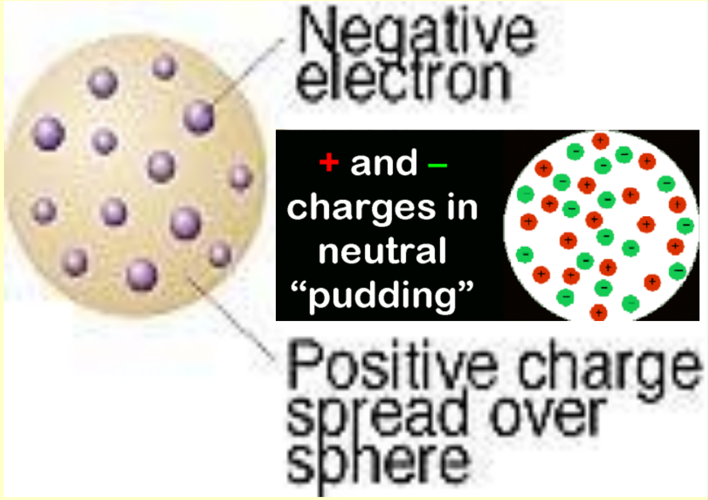
Early Atomic Models: Hard Sphere; Plum Pudding

5th Century B.C.
Hard **Sphere** Model



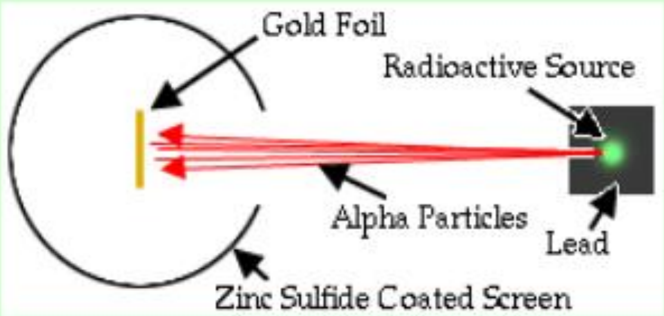
Greek Philosopher Democritus proposed that every form of matter is made of very tiny pieces or <u>indivisible</u> building blocks, which he called ATOMS.

1897 – Plum Pudding Model



J. J. Thomson reasoned that because electrons comprise only a very small fraction of the mass of an atom, they probably were responsible for an equally small fraction of the atom's size.

1907 – Testing the Plum Pudding Model

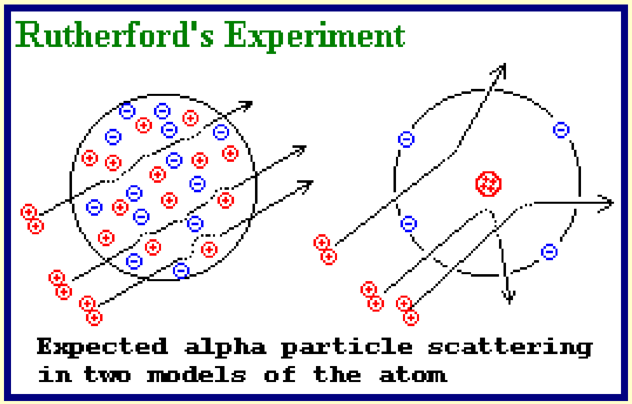


Ernest Rutherford sent alpha particles from a radioactive source through a thin foil to observe the distribution of scattered particles.

Nuclear Atom; Soft scattering; Hard scattering

1907 – Nuclear Atom

Rutherford expected the alpha particles to be only slightly deflected when passing through the "plum pudding" atoms.



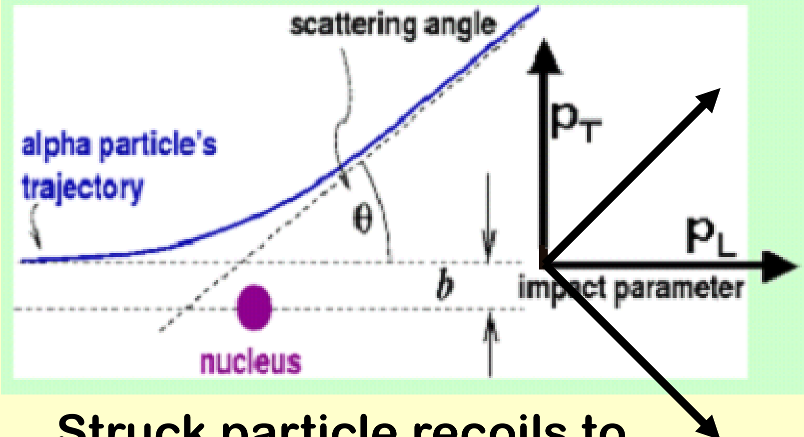
Instead .... they were deflected to large angles.

This proved that a massive nucleus was at the center.

Rutherford was astonished and said: "It was almost as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

Transverse Momentum p_T

Longitudinal Momentum p_L



Struck particle recoils to conserve linear momentum (total p_T is always 0)

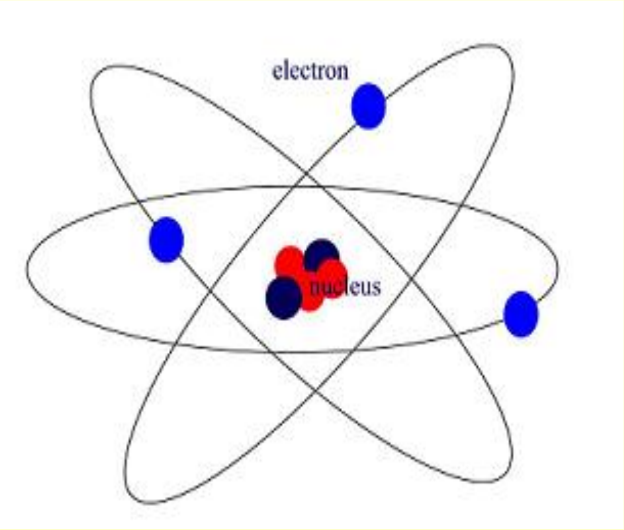
Soft Scattering: Low p_T

Hard Scattering: High p_T

(hard scattering implies substructure, that is something smaller inside).

Bohr Planetary Model – DeBroglie Electron Waves

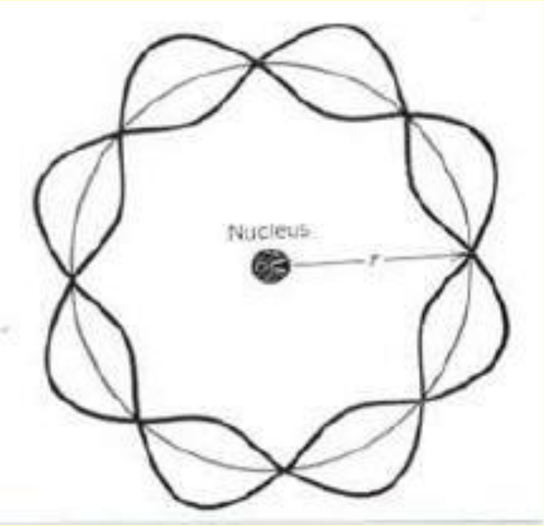
1913
Planetary Atom



Neils Bohr suggested that the electrons in an atom might be orbiting the nucleus, much like the planets in our solar system orbit the sun ....

but in non-radiating orbits!

1923
Standing Electron Waves

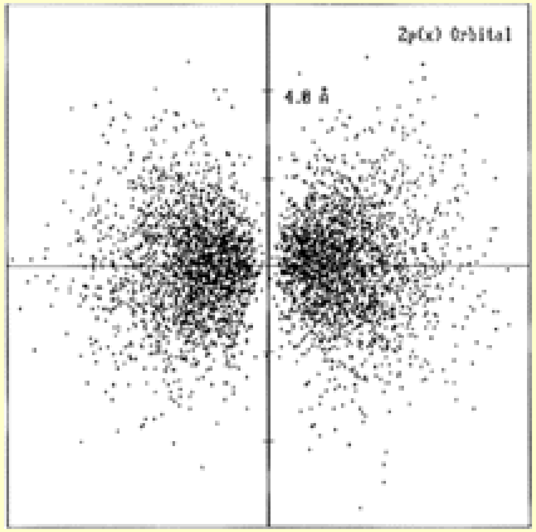


Louis de Broglie proposed the fascinating idea that matter actually consists of *waves*.

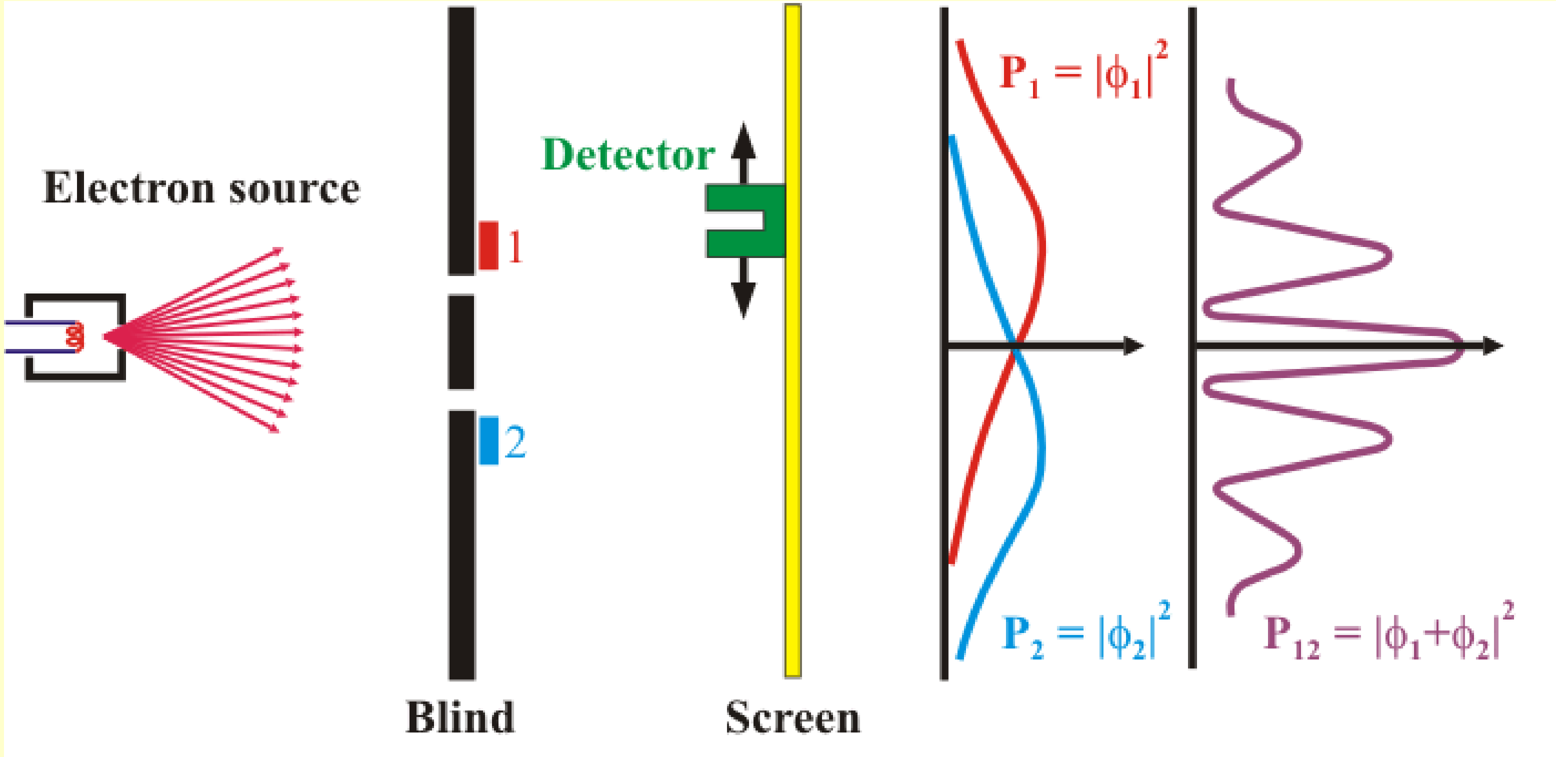
For example, the electrons in an atom form standing electron waves.

1926
Wave Mechanics

Erwin Schroedinger showed later that probability distributions can tell where the *particle* is most likely to be.



Electron Diffraction



Wave-Particle Dualism: Electrons exhibit both wave and particle aspects.

Energy: $E = h f = h v_e / \lambda$

Momentum: $p = h f / v_e = h / \lambda$

Wave-Particle Dualism

Experiments have shown that things we usually think of as waves also act like particles and that things we usually think of as particles also act like waves.

Light Wave ←→ Photon
Electron Wave ←→ Electron

This does <u>NOT</u> mean that all things are "wavicles" An electron (e.g., one bound in an atom) acts as either 100% particle or 100% wave.

Principle of <u>Complimentarity</u>: No experiment can simultaneously show both wave and particle aspects at the same point in space and time.

Quantum Mechanics Quotes

Most physicists are very naive; most still believe in real waves or real particles. ***– A. Zeilinger***

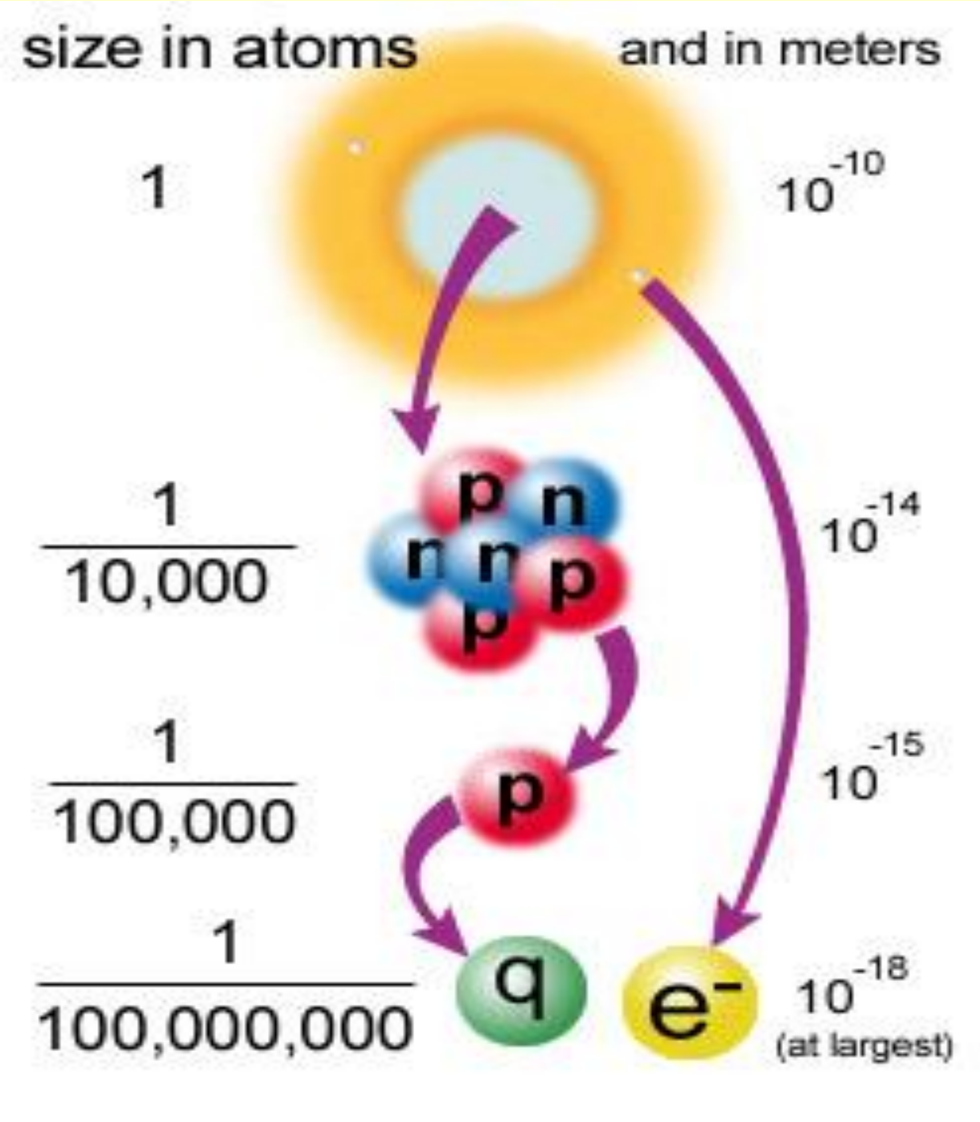
Quantum phenomena are neither waves nor particles, but are intrinsically undefined until the moment they are measured. **– J. Wheeler**

God does not play dice with the universe. – ***A. Einstein***

It is not the job of scientists to prescribe to God how He should run the world. ***– N. Bohr***

Bohr said that if you aren't confused by quantum mechanics, then you haven't really understood it
– J. Wheeler

Atom, Nucleus, Nucleon, Parton, Electron

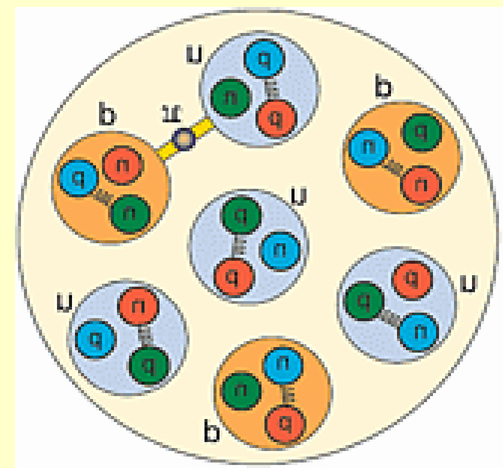


smaller parts

Atom:
Nucleus & Electrons
~ 0.1 nm

Nucleus ~ 10 fm

Nucleons:
Protons
Neutrons
~1 fm



Partons
Quarks & Gluons
(Size of Electrons ~ 1 am)

Mechanics: Classical, Quantum, Relativistic

Mechanics	Energy	Momentum	Conserved
Classical [Newtonian] (human size and speed)	Kinetic: $E = 1/2\, m\, v^2$ Potential: $T = m\, g\, h$ Total: $E = T + K$	Linear: $p = m\, v$ Orbital: $l = m\, v\, r$	Energy, Mass, Momentum, Waves, Particles, Size, Time
Quantum (very small)	$E = h\, \nu$ $= h\, c / \lambda$ (Wave-Particle Duality)	$p = h / \lambda$	Energy, Momentum [stuff is not!]
Relativistic (very fast)	$E = mc^2 = \gamma\, m_0 c^2$ $= \sqrt{p^2c^2 + m_0^2 c^4}$	$p = m\, v$ $p = \gamma\, m_0\, v$	Mass/Energy, Momentum [stuff is not!]

$$\gamma = 1 / \sqrt{1 - v^2 / c^2}$$

Main Message:

Total energy and momentum are always conserved, but for very small (quantum) and very fast (relativistic) mechanics, the "stuff" that carries the energy and momentum is not conserved and not even well defined.

$$E = h\, \nu$$
$$= h\, c / \lambda$$

$$E = m\, c^2$$

Elements and Isotopes

Atomic Mass (A)
= Z + N

Element (C):

$$^{12}_{\;6}C_{6}$$

Atomic Number (Z)
= number of protons (p)

Neutron Number (N)
= number of neutrons (n)

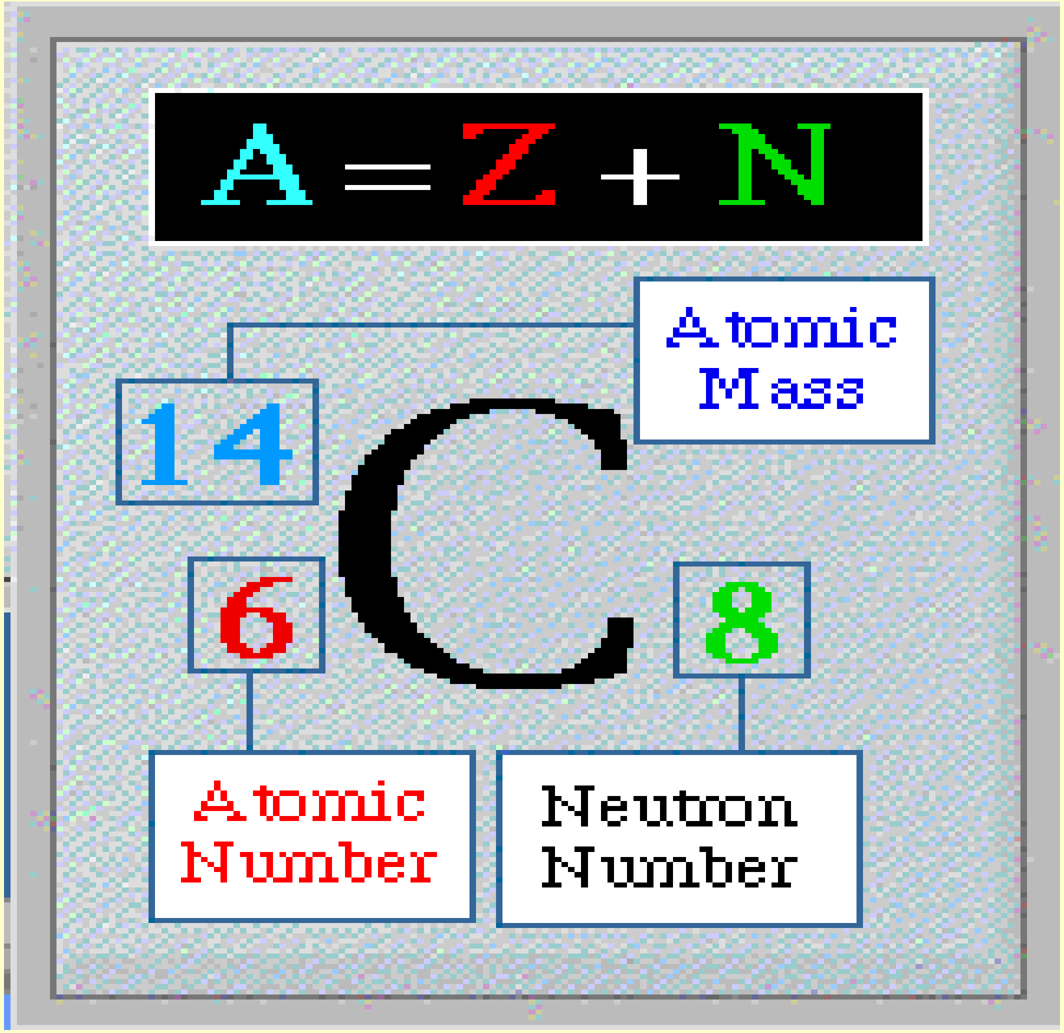
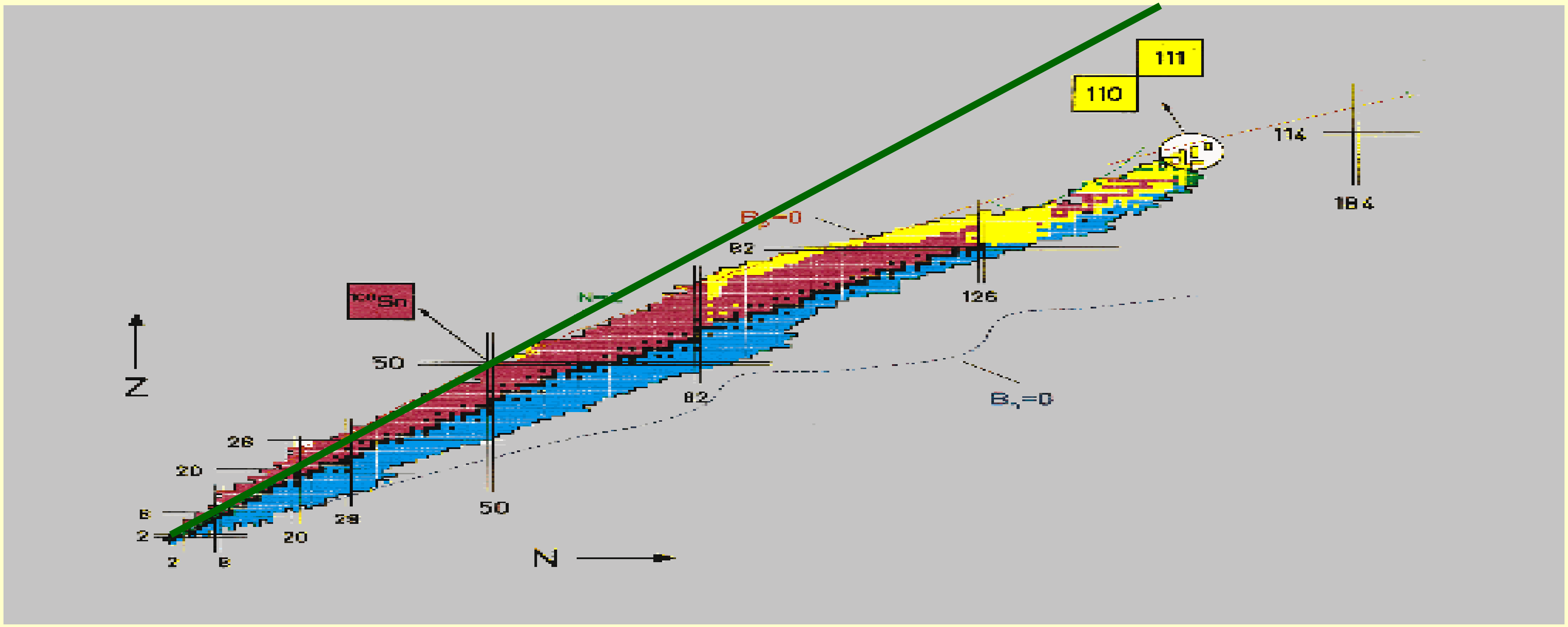


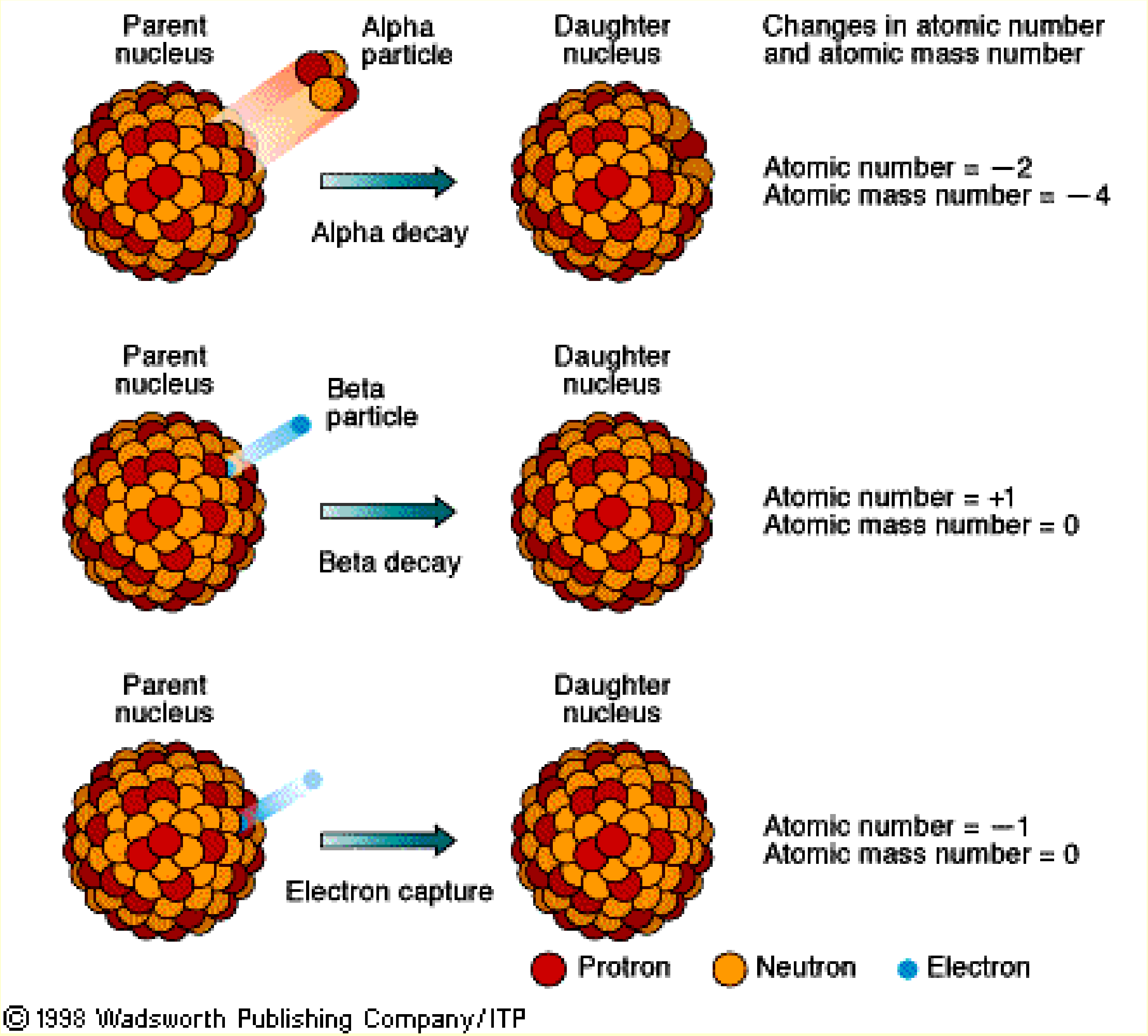
Chart of the Nuclides (Z vs. N)



Isotopes are nuclei with the same Atomic Number Z (protons), but different Neutron Number N (neutrons). Light elements usually have about the same N as Z, but heavier elements have more neutrons (higher N) than protons (lower Z).

Radioactive decay can change Z or M

Some forms of radioactive decay can change the atomic number (Z) or mass (M) of the primary nucleus.

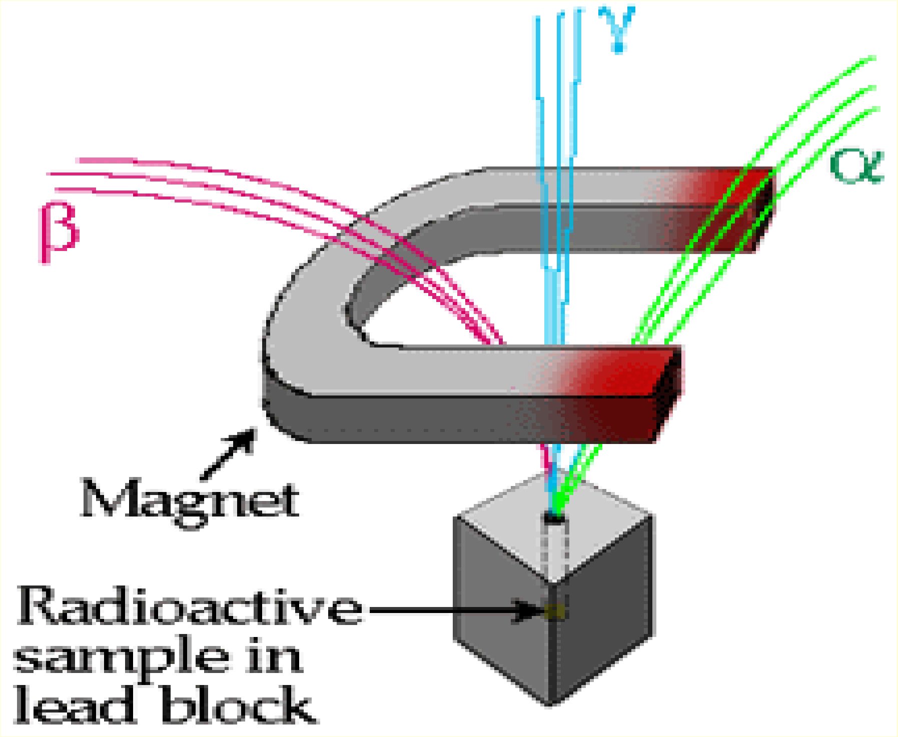


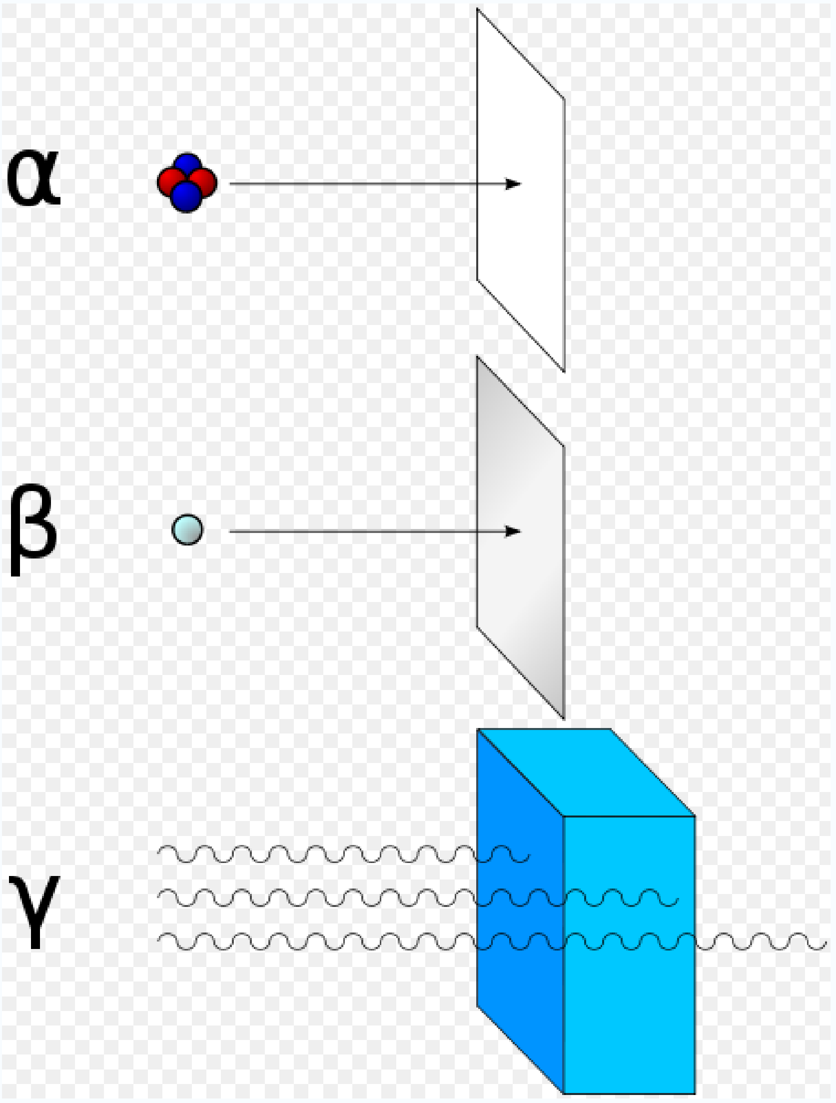
Three common forms of radioactive decay

<u>Alpha</u> Nucleus of normal He isotope;
2 protons and 2 neutrons (charge =+2).

<u>Beta</u> Electron (charge = -1)

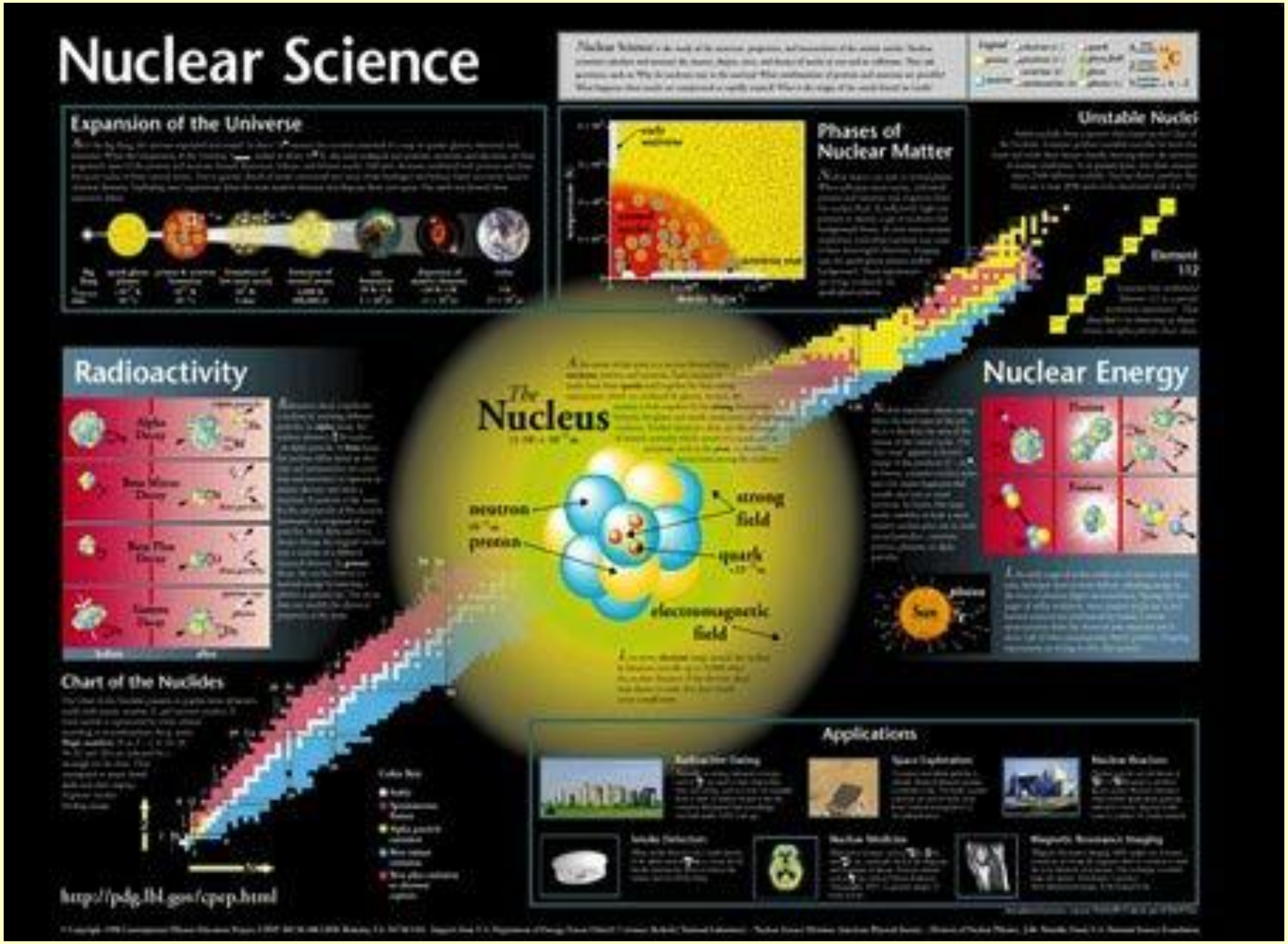
<u>Gamma</u> Photon (particle of light)
called gamma-ray from nucleus,
or x-ray from atom.





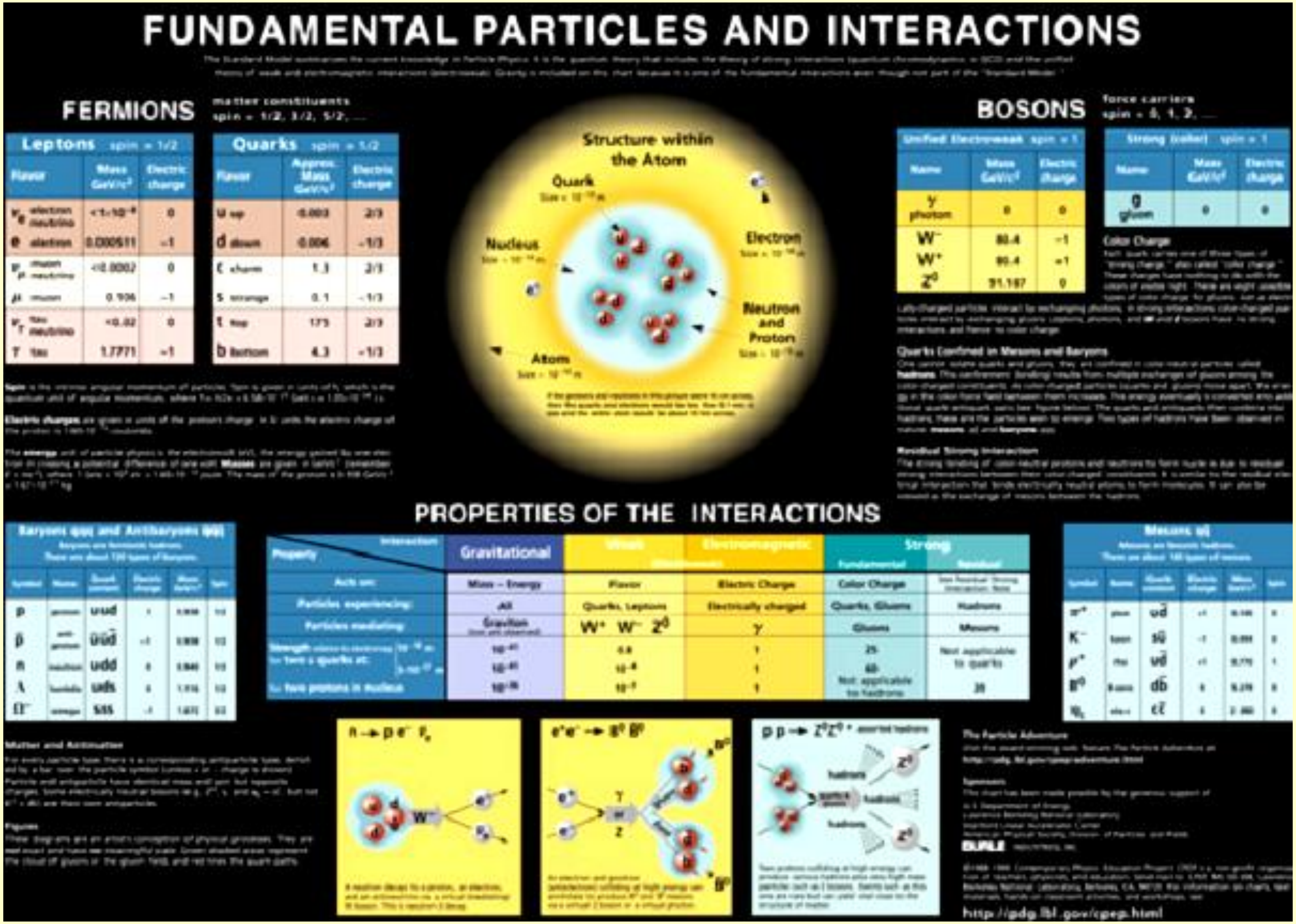
Nuclear Science Web Pages

The ABC's of Nuclear Science http://www.lbl.gov/abc/



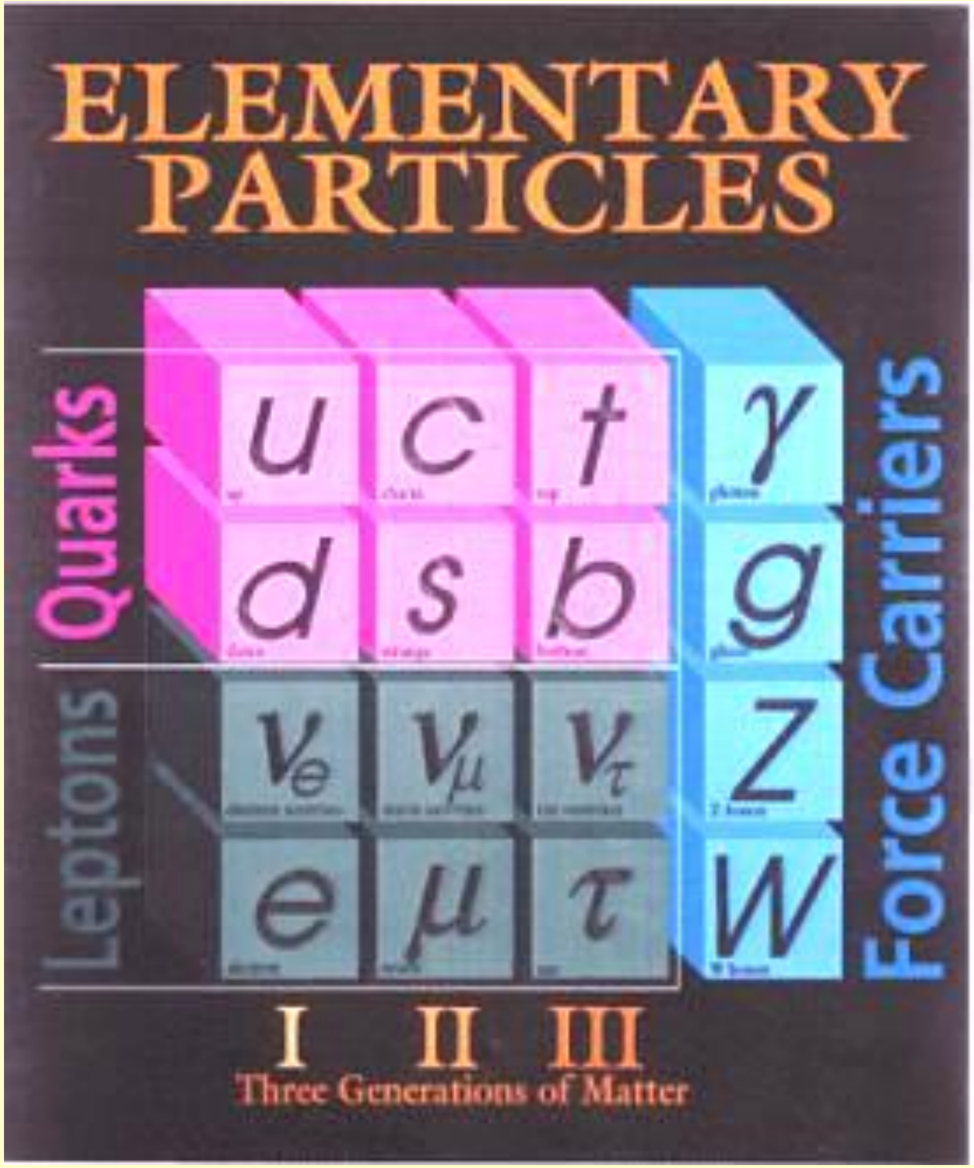
The Nuclear Science Wall Chart and tour of Nuclear Science

The Standard Model of



http://particleadventure.org/particleadventure/ http://www.cpepweb.org/particles.html

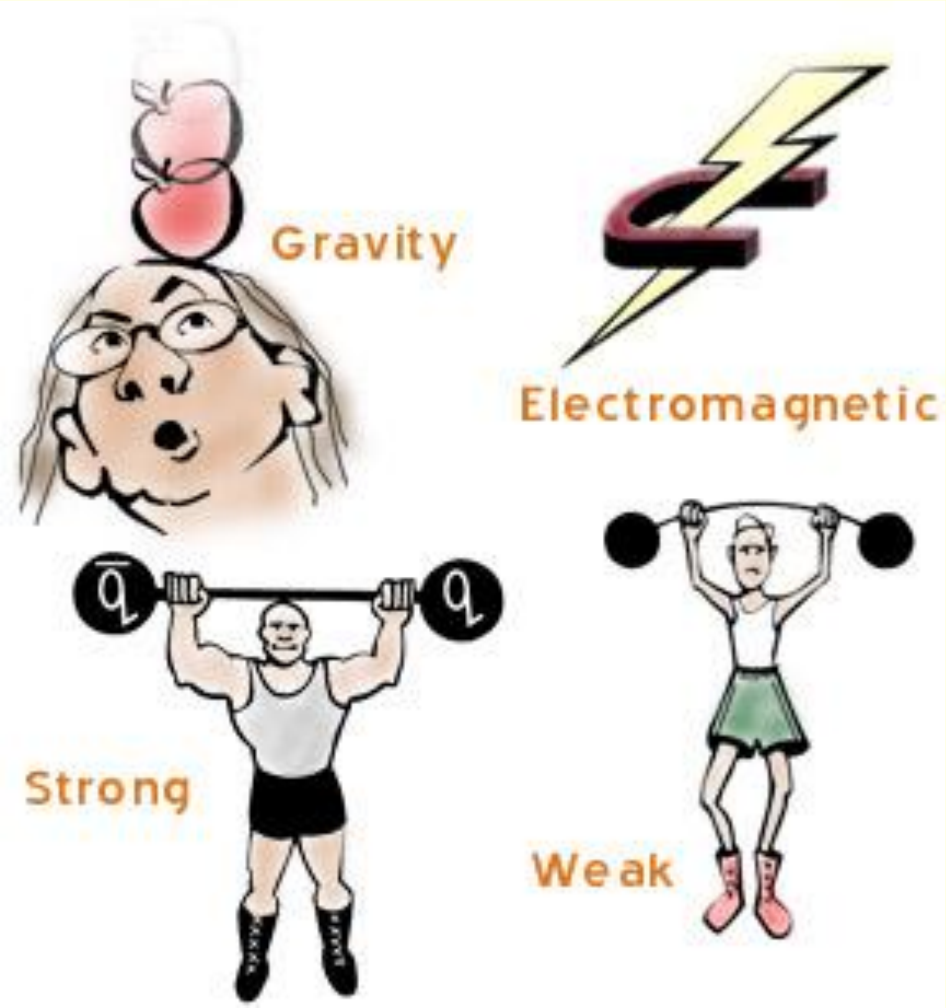
Particles and Fields

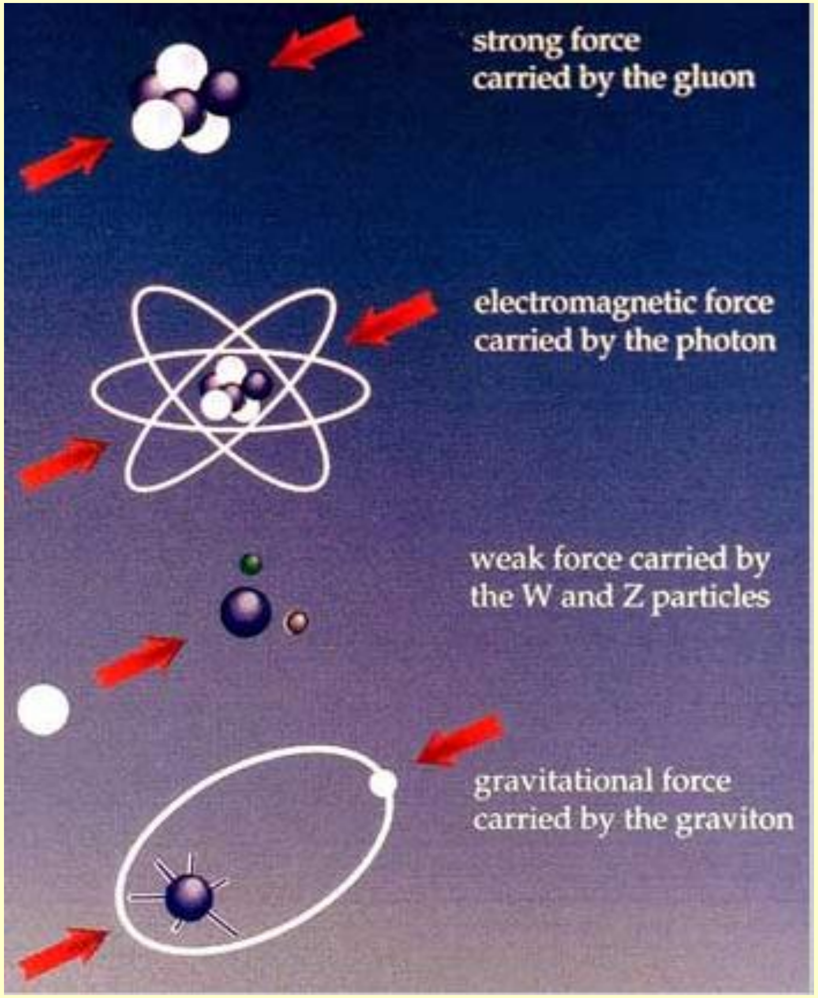


Matter particles		
QUARKS	up	u
	down	d
	charm	c
	strange	s
	top	t
	bottom	b
LEPTONS	electron neutrino	ν_e
	electron	e
	muon neutrino	ν_μ
	muon	μ
	tau neutrino	ν_τ
	tau	τ

Force carriers	
the photon	γ
vector bosons	W^+, W^-, Z^0
gluons (8)	g

Four Fundamental Interactions





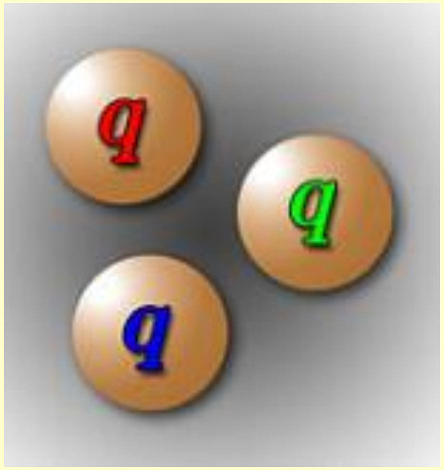
http://particleadventure.org/particleadventure/

Baryons (protons, neutrons, etc.)

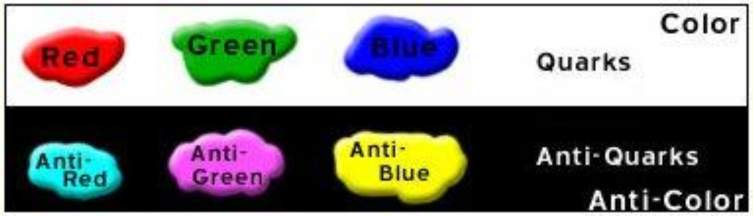
Sample **Fermionic Hadrons**

Baryons (qqq) and Anti-baryon ($\overline{qqq}$)

Symbol	Name	Quark Content	Electric Charge	Mass (GeV/c^2)	Spin
p	proton	uud	+1	0.938	1/2
$\overline{p}$	anti-proton	$\overline{uud}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2



Color neutral



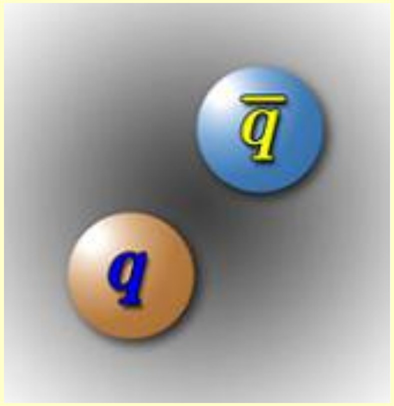
Color neutral

Meson (pions, kaons, etc.)

***Sample* Bosonic Hadrons**
Mesons ($q\bar{q}$)

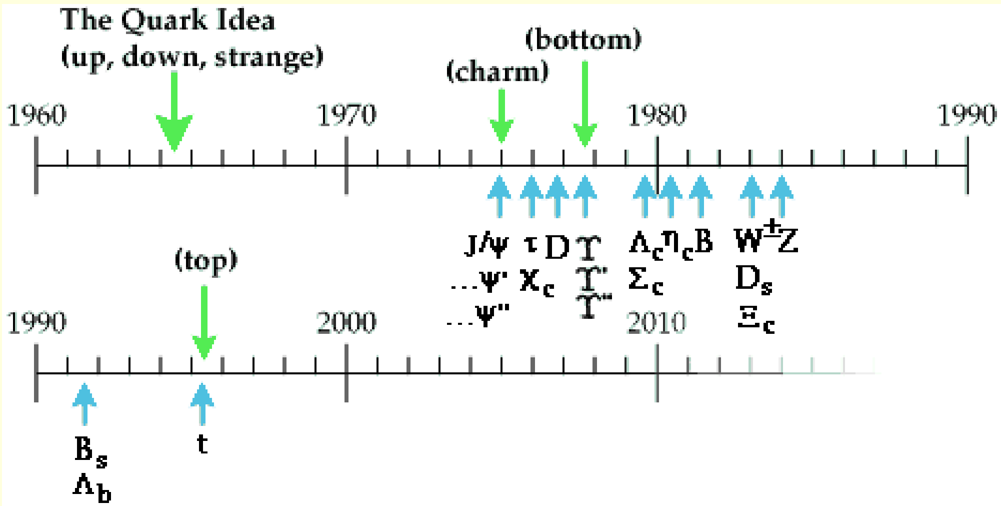
Symbol	Name	Quark Content	Electric Charge	Mass (GeV/c^2)	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
D^+	D+	$c\bar{d}$	+1	1.869	0
η_c	eta-c	$c\bar{c}$	0	2.979	0

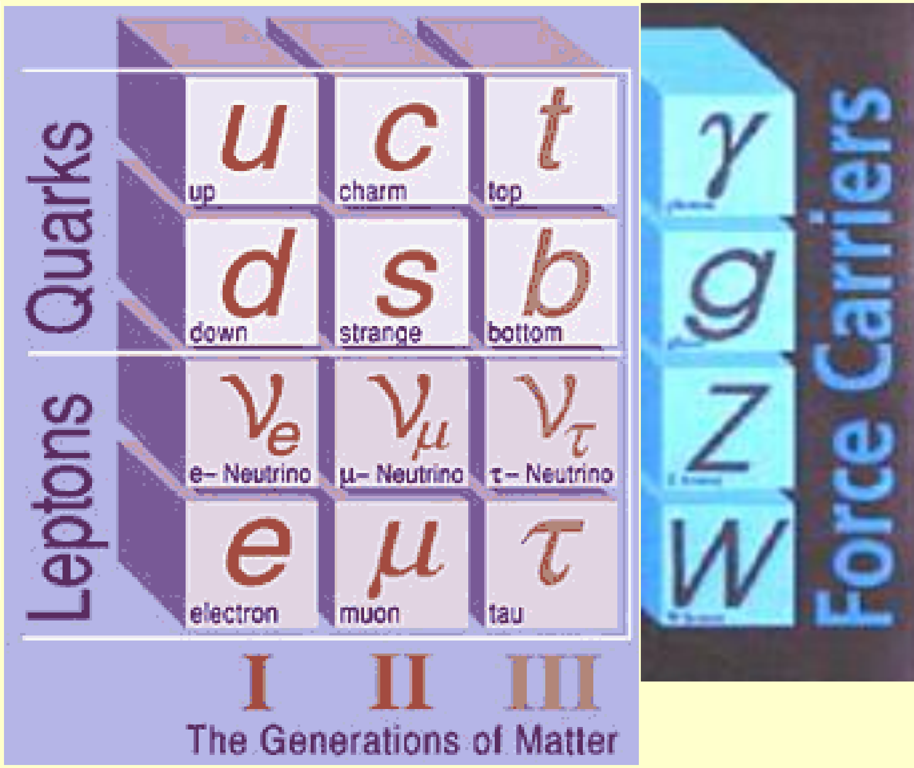
Color neutral



Standard Model: Leptons, Quarks, and Gluons

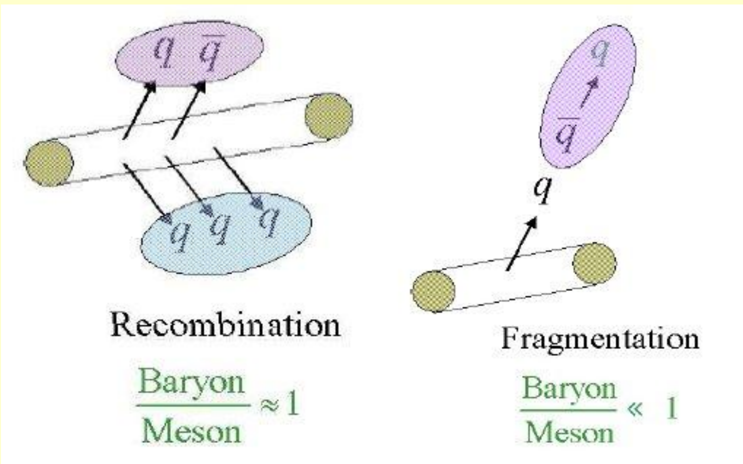
Particles discovered 1964 - present:



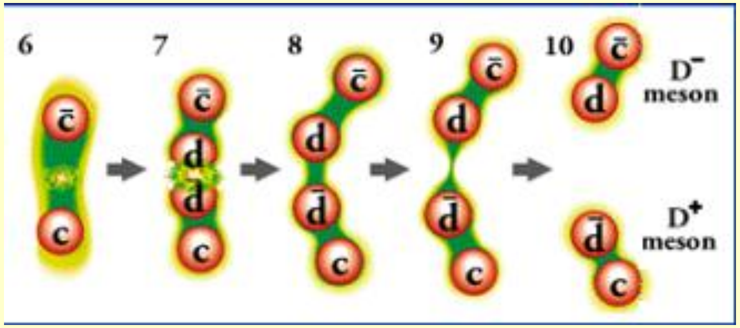


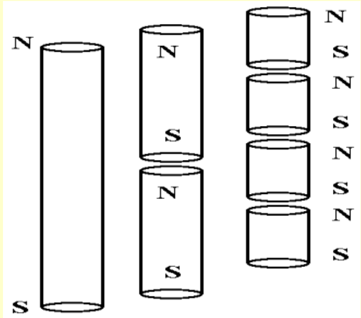
Mesons ($q\bar{q}$) Pion (π) kaon (K), J/ψ, φ, ω

Baryons (qqq) and Anti-baryon ($\overline{qqq}$) p, n, Λ, …



Cannot separate quarks (or poles of magnets)





RHIC Accelerator Complex and Detectors

Inside the RHIC tunnel

Relativistic Heavy Ion Collider

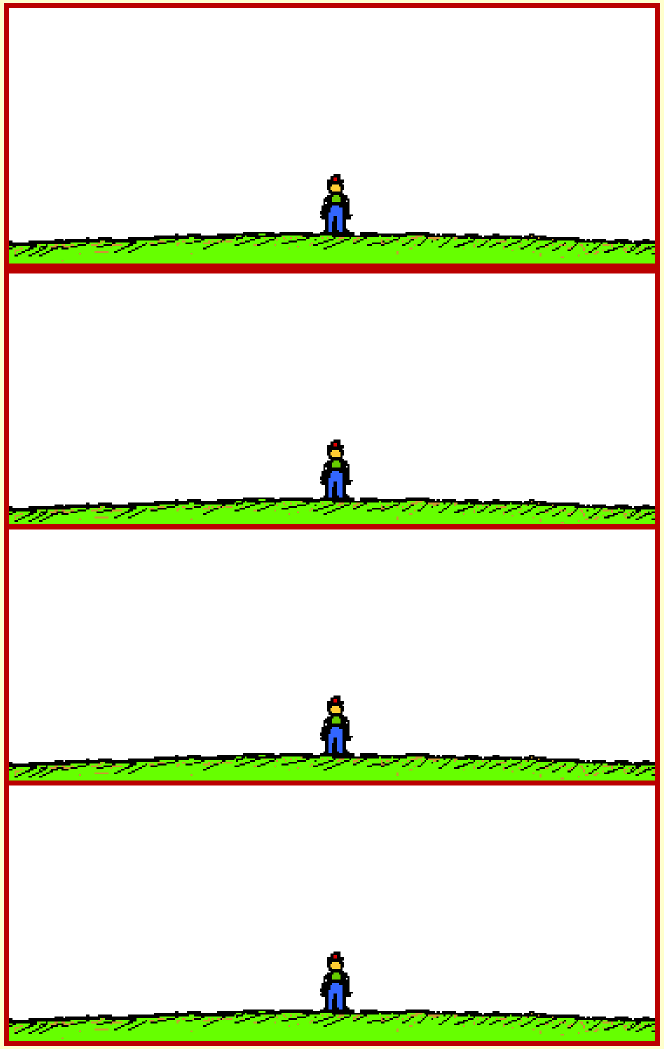
Relativistic: *Something traveling at nearly the speed of light*

Heavy Ion: *Typically fully-stripped gold ions (bare gold nucleii)*

Collider: *Two ion beams aimed at each other to hit head-on.*

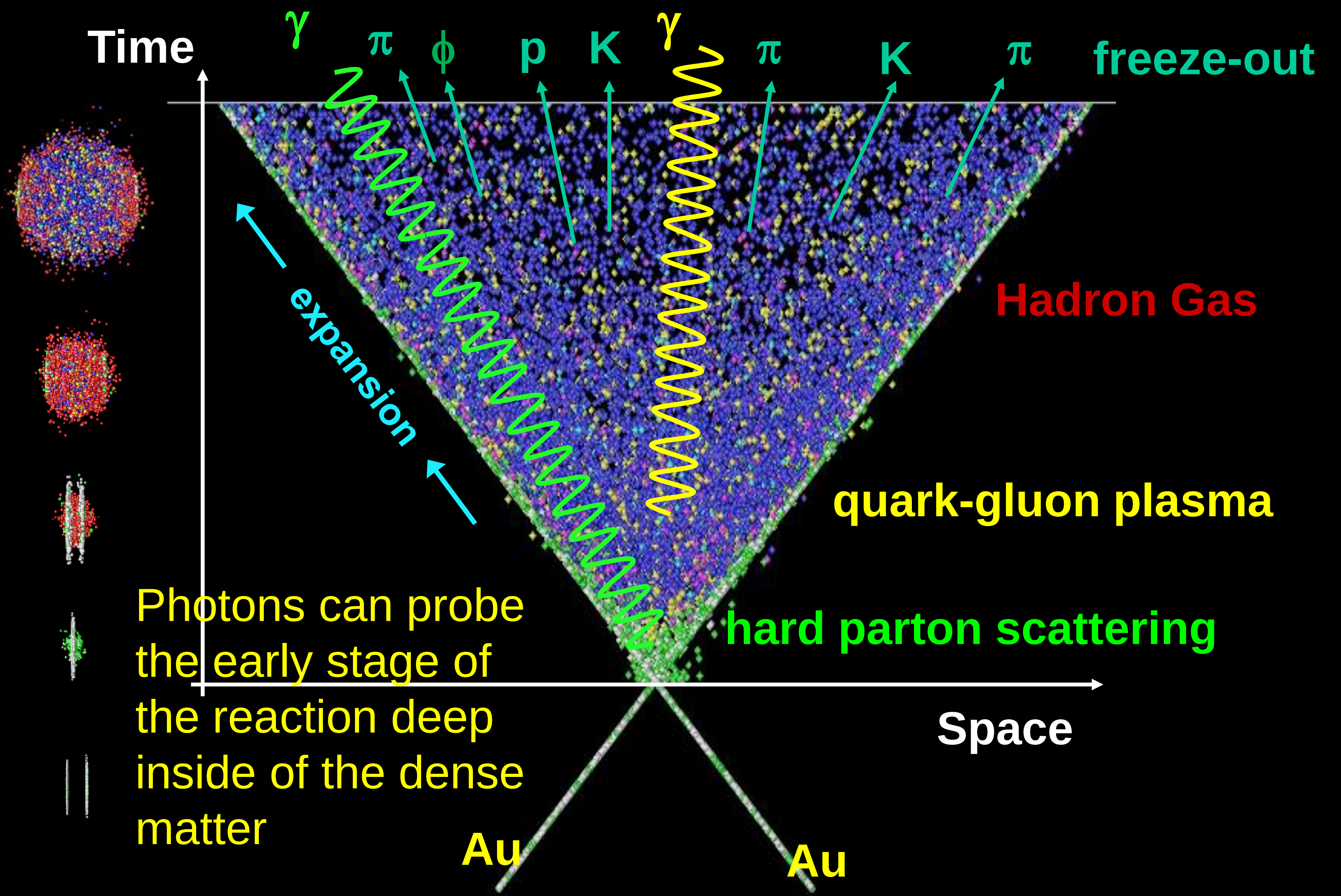
RHIC by the numbers:
Circumference 3.83 km = 2.38 miles
Maximum energies 100+100 GeV heavy ions,
250+250 GeV protons
Circulation frequency 80,000/sec (80 kHz)
Collision frequency (x100) 8 Mhz
Ion velocity 99.9995% speed of light.

Relativistic Length Contraction



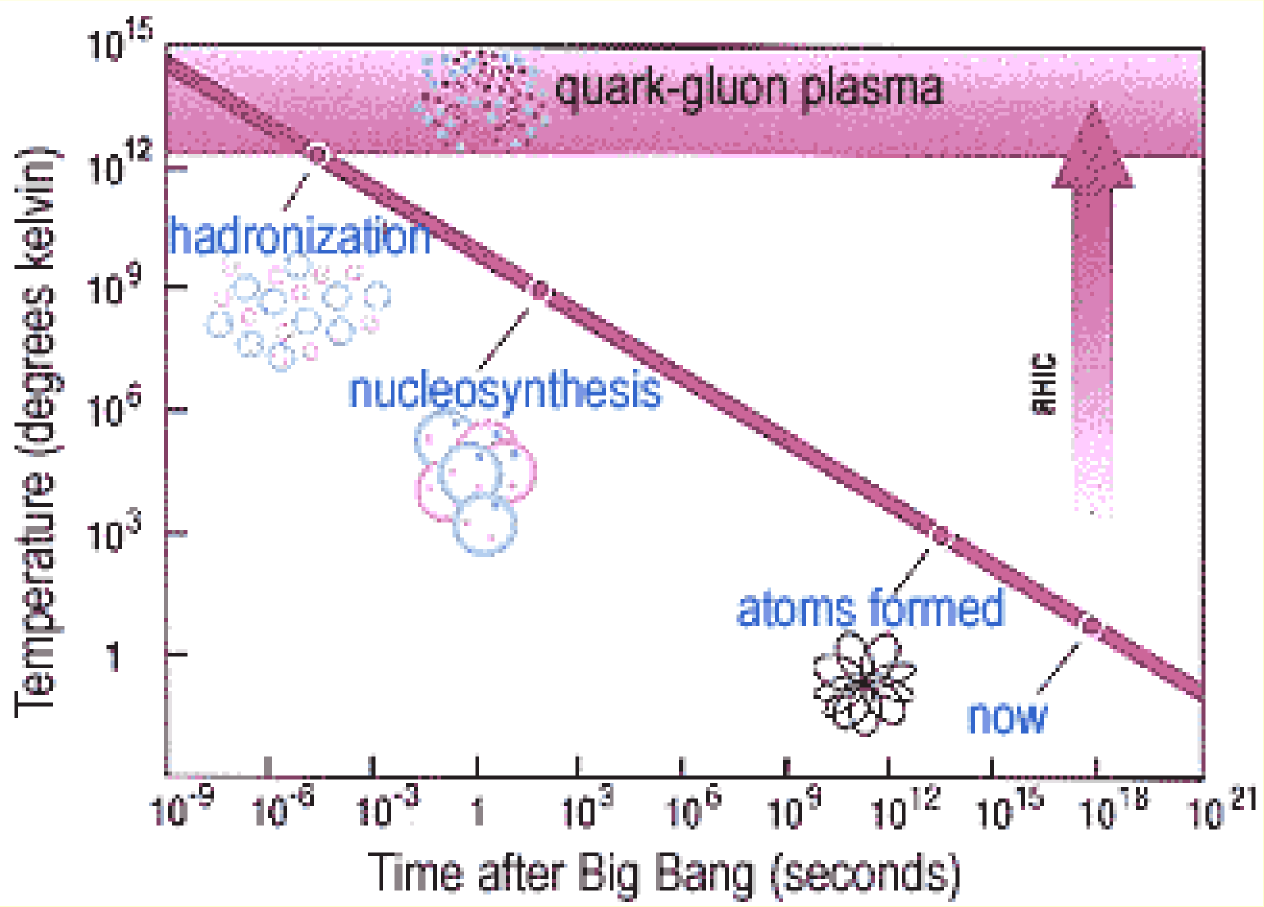
Speed of Spaceship	Observed Length	Observed Height
At rest	200 ft	40 ft
10 % the speed of light	199 ft	40 ft
86.5 % the speed of light	100 ft	40 ft
99 % the speed of light	28 ft	40 ft
99.99 % the speed of light	3 ft	40 ft

Photon Probe of Nuclear Collisions



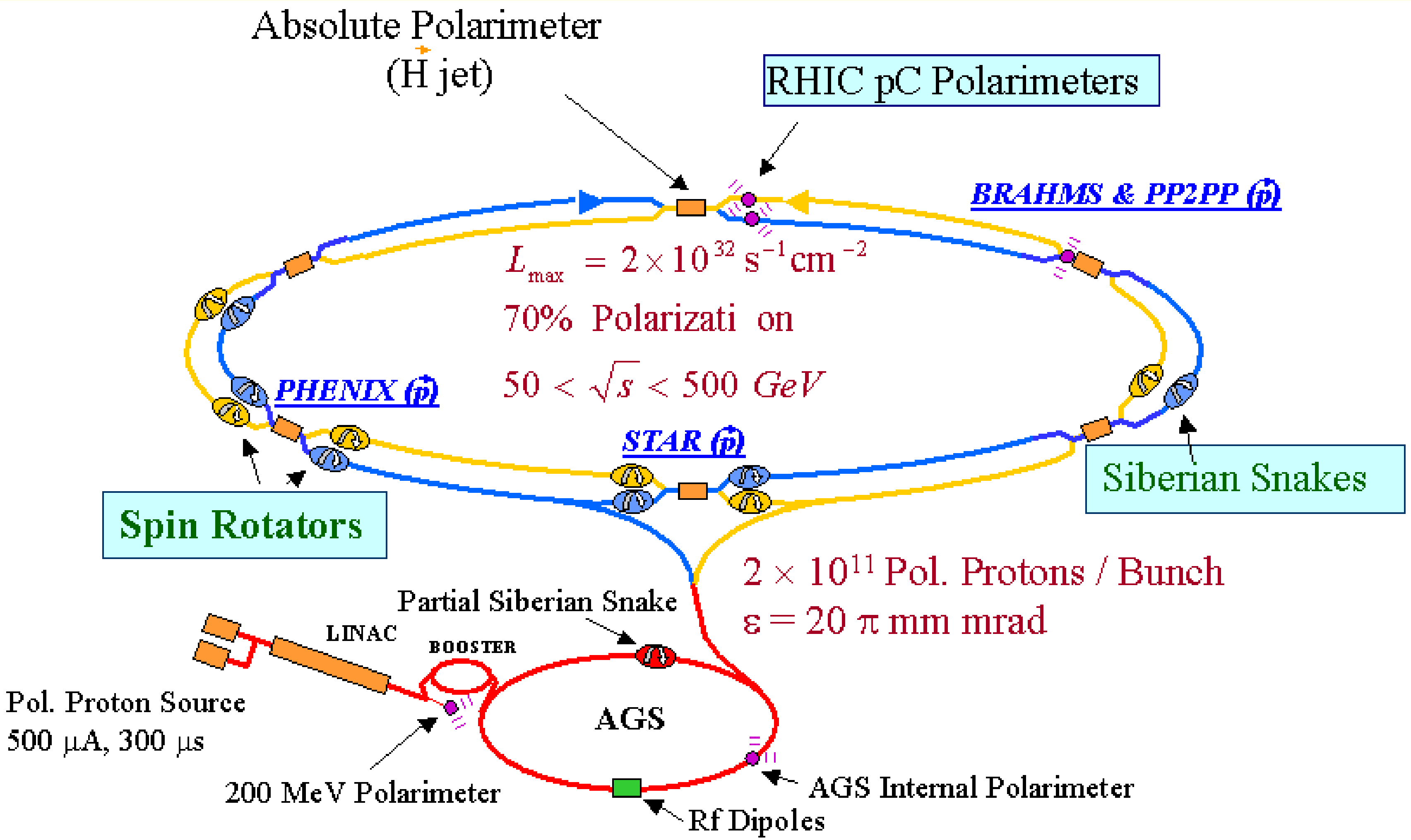
Photons can probe the early stage of the reaction deep inside of the dense matter

RHIC As A Time Machine



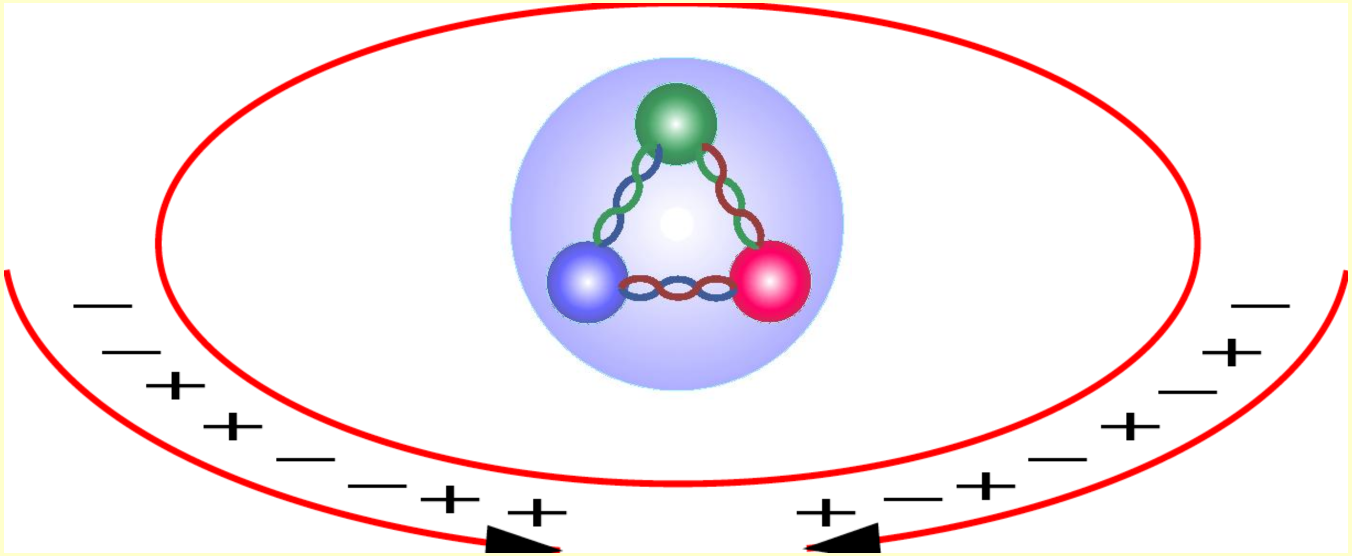
- Temperature of collisions is about 4 trillion degrees
  500,000 times hotter than the center of the sun!
- Super-high temperatures reminiscent of early universe!

RHIC is World's first (and only) polarized proton collider



RHIC accelerates heavy ions to 100 GeV/A
and polarized protons to 250 GeV

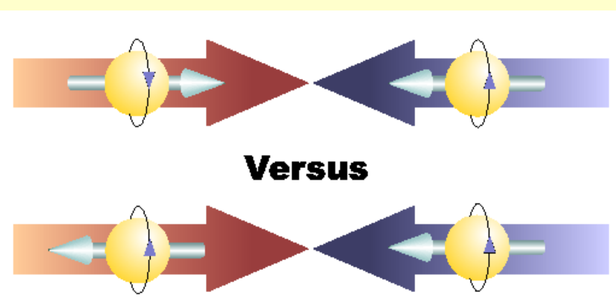
Spin Physics (measure spin substructure)

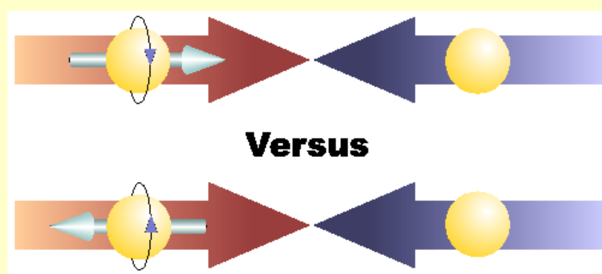


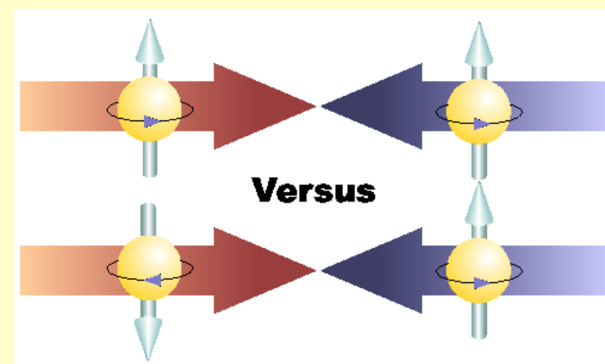
$$A_{LL} \rightarrow \frac{\Delta G}{G}$$

$$A_L^{W^\pm} \rightarrow \frac{\Delta q}{q}; \frac{\Delta \bar{q}}{\bar{q}}$$

$$A_N, A_{TT}$$



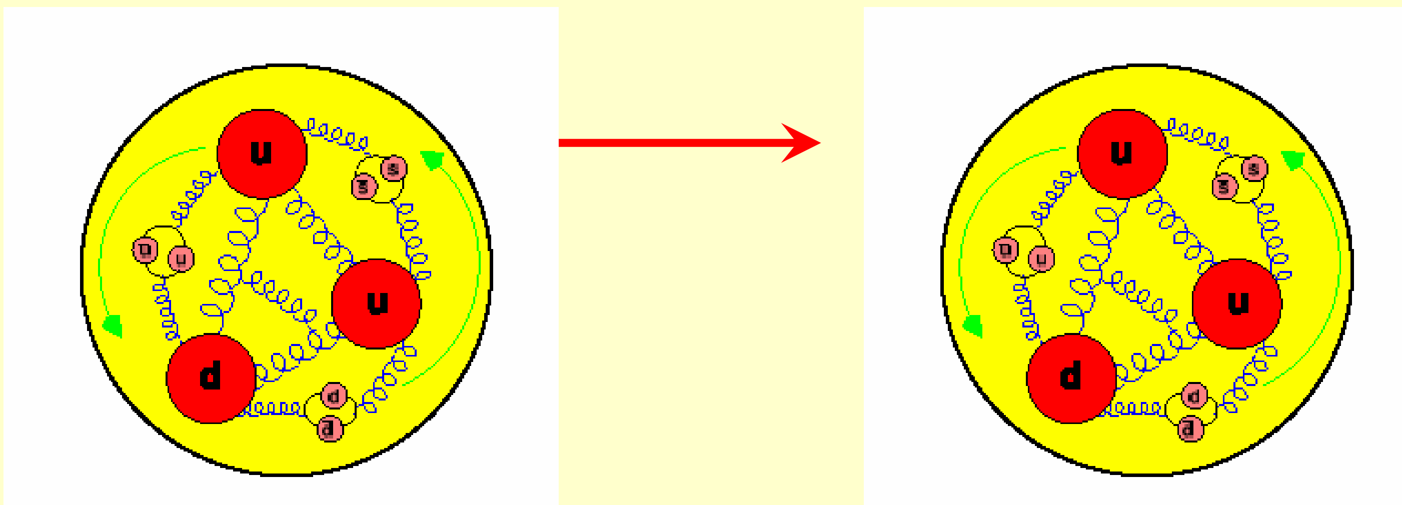




Studying Proton Structure with Quark and Gluon Probes

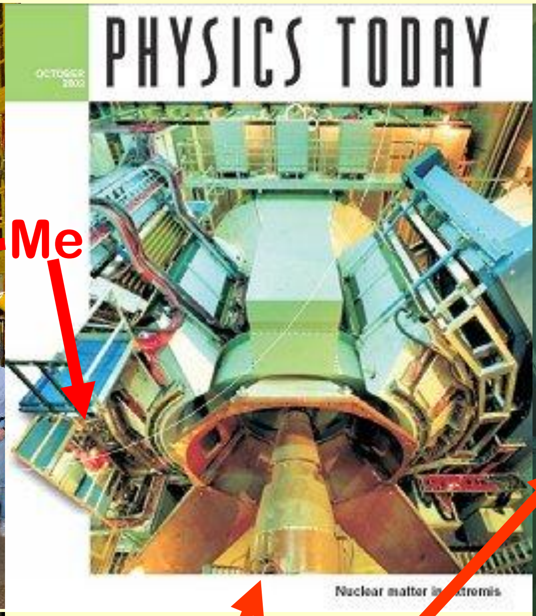
$$\frac{1}{2} = \frac{1}{2} \cdot \Delta\Sigma \; + \; \Delta G + L_{G+q}$$

At ultra-relativistic energies the proton represents a jet of quark and gluon probes



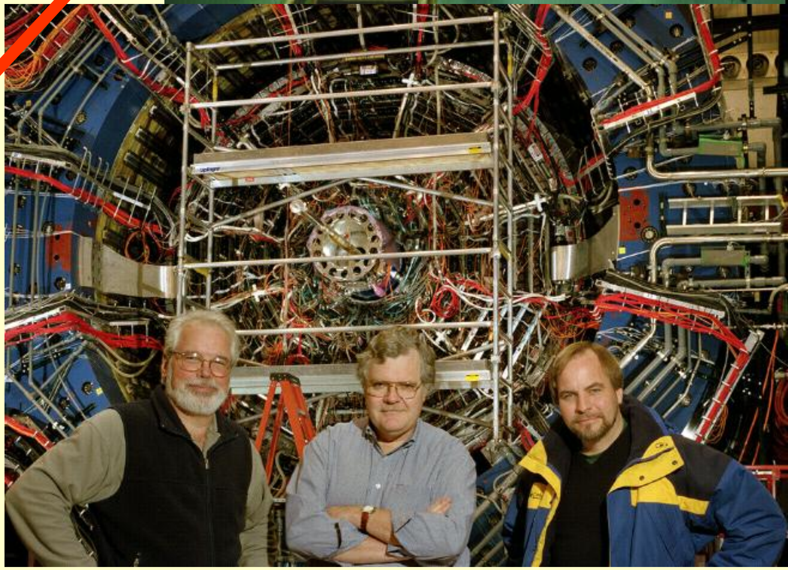
PHENIX, STAR, (formerly PHOBOS, BRAHMS)

Me



PHENIX

STAR

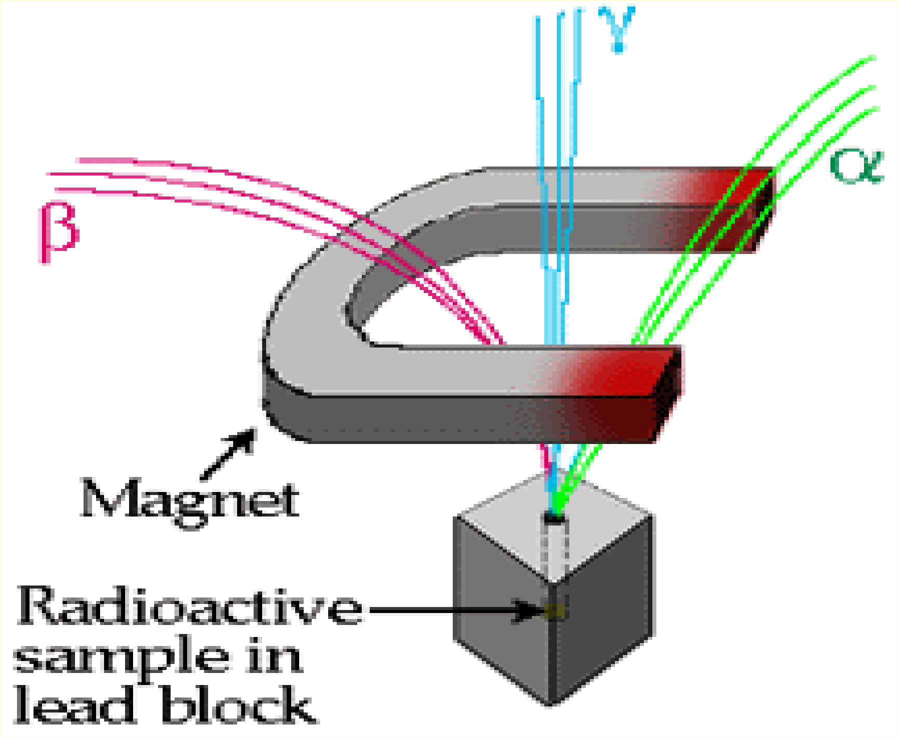


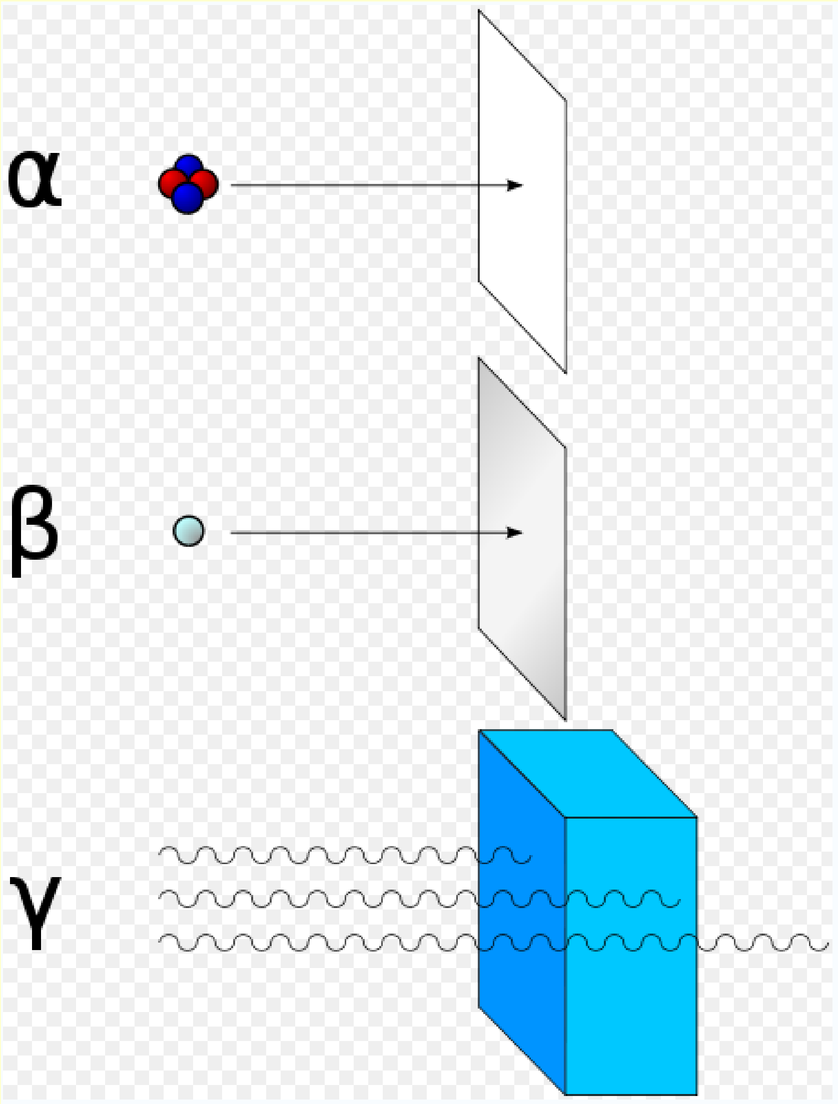
Three common forms of radioactive decay

Alpha Nucleus of normal He isotope;
2 protons and 2 neutrons (charge =+2).

Beta Electron (charge = -1)

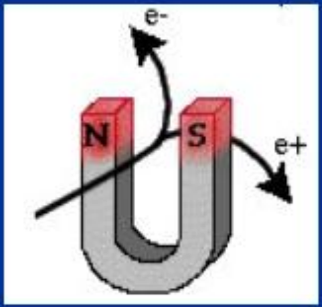
Gamma Photon (particle of light)
called gamma-ray from nucleus,
or x-ray from atom.



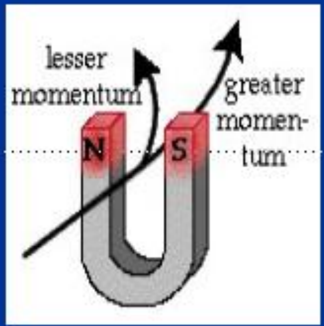


Tracking Detectors Measure Charge and Momentum

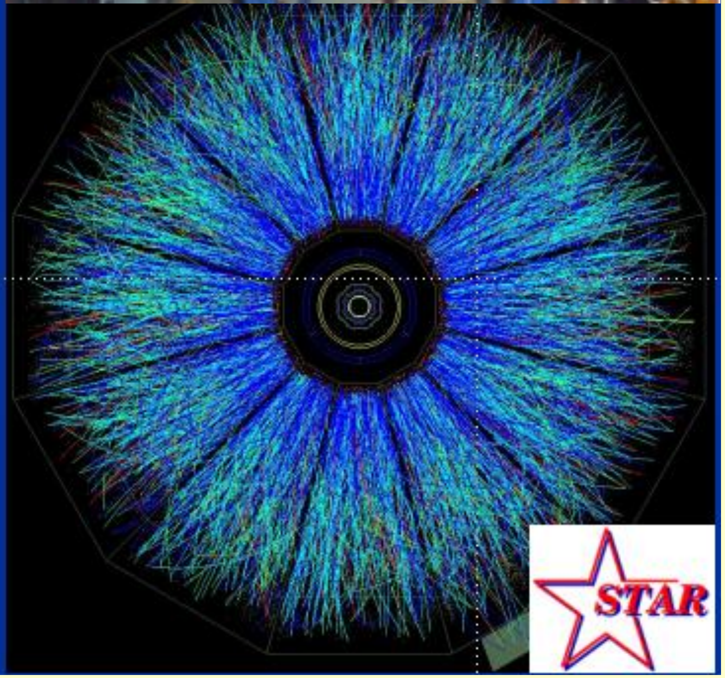
Event Displays



Left/Right tells charge

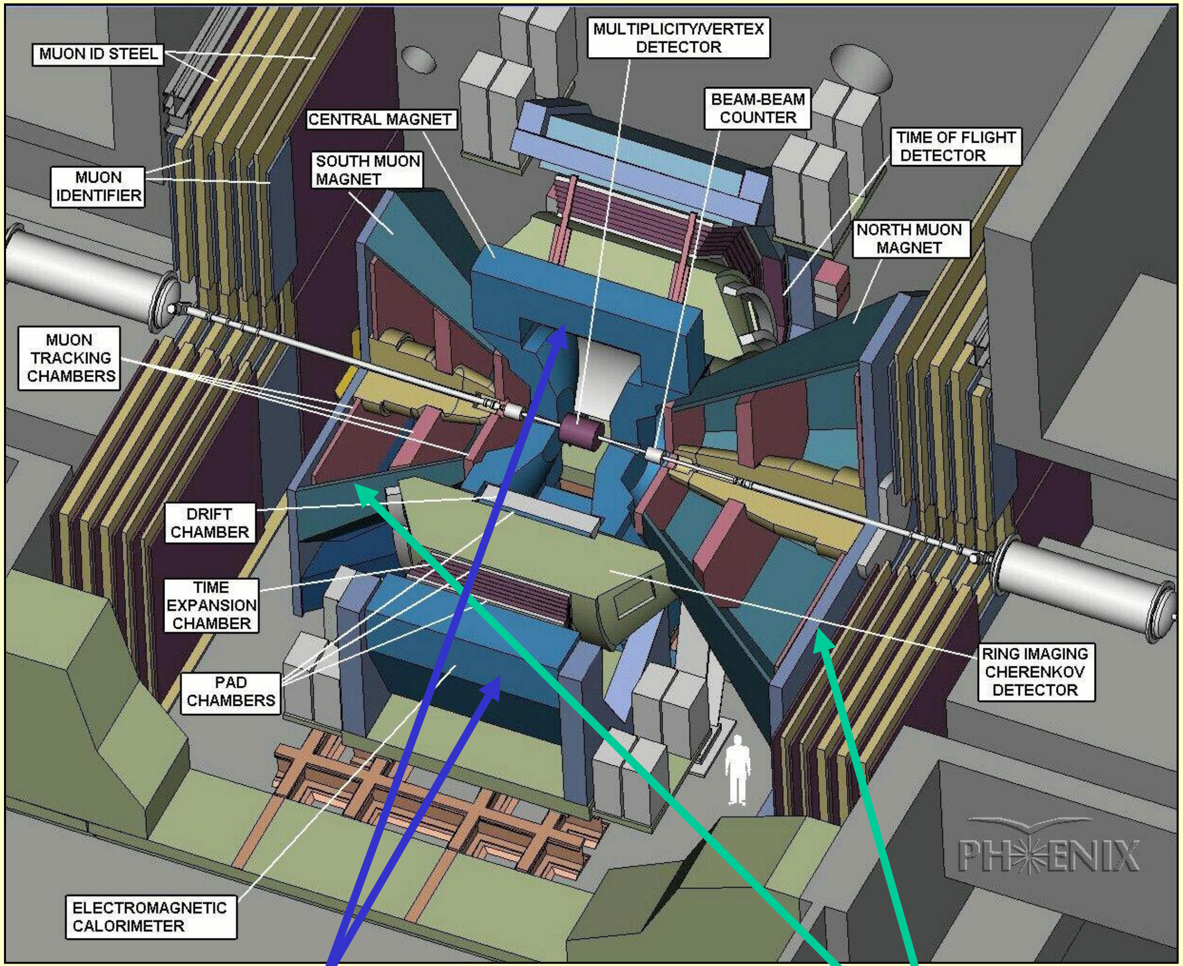


Curvature is proportional to 1/p



The PHENIX Detector at RHIC

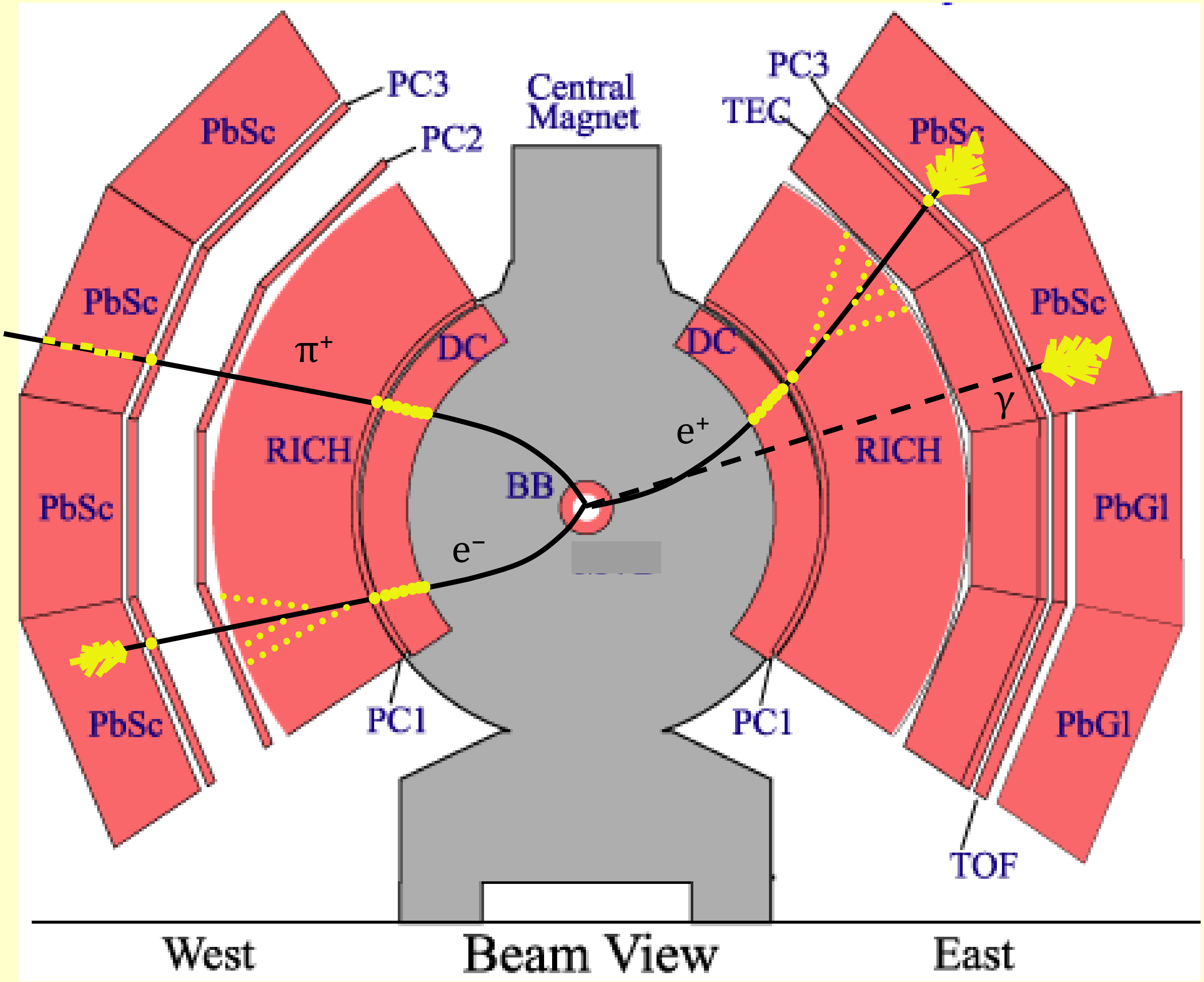
- Two Central Arm Spectrometers to measure hadrons, electrons, photons
- Two Forward Spectrometers to measure muons
- All four used to identify particle type; measure momentum.



two central electron/photon/hadron spectrometers

two forward muon spectrometers

PHENIX: Tracking & Particle Identification

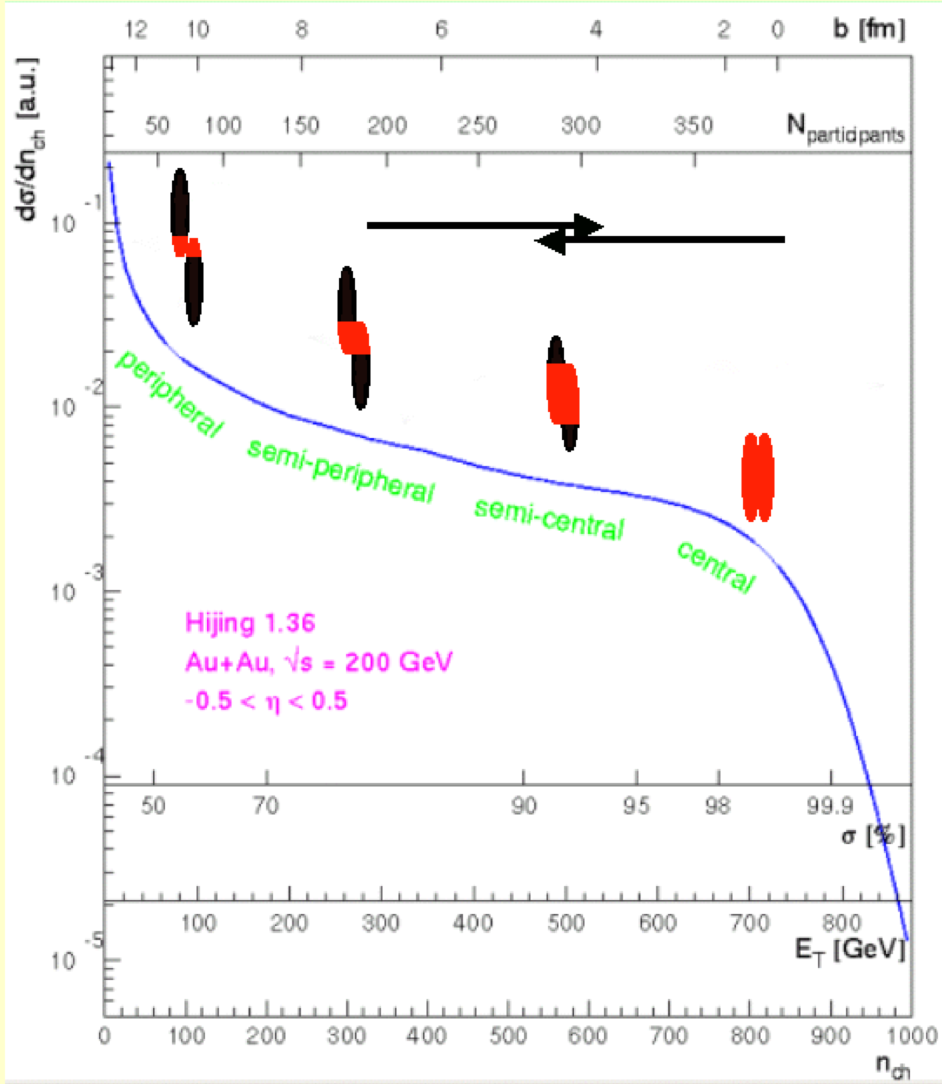


Multiplicity, Centrality, Peripheral, Central

Multiplicity:

A large number or wide range (of something).

At RHIC: the something is particles



Centrality:

The state of being central; tendency towards a center.

RHIC collisions :

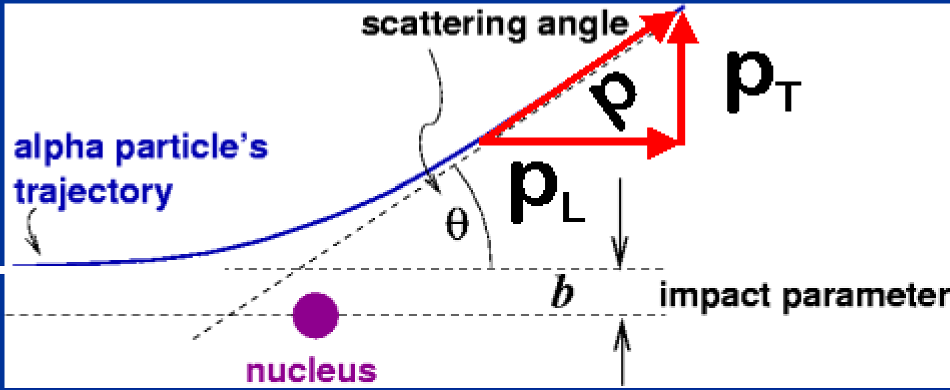
peripheral

semi-peripheral

semi-central

most central

Soft and Hard Scattering: What happens at high p_T?



Transverse Momentum $\boxed{p_T}$

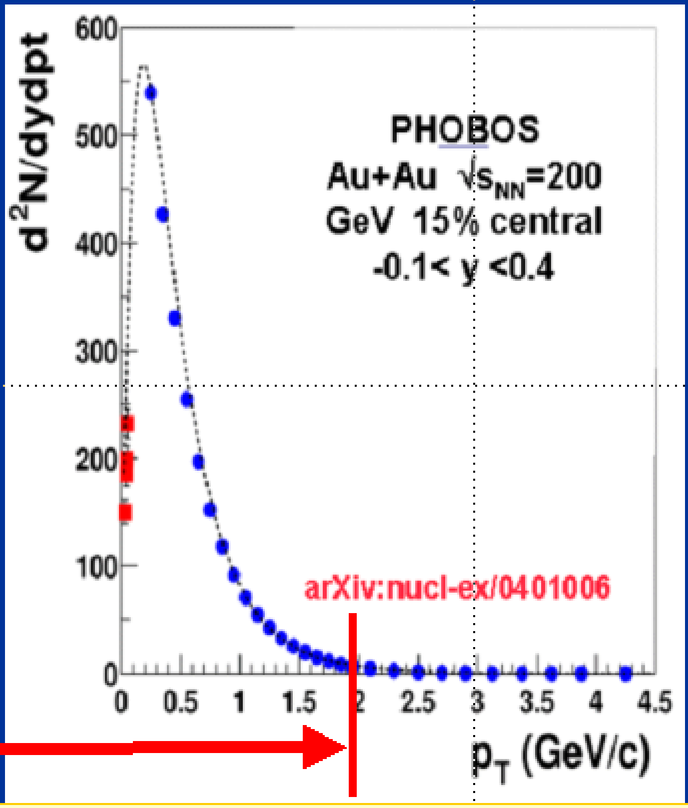
Longitudinal Momentum

Soft Scattering:
- Low p_T like in plum pudding model prediction.

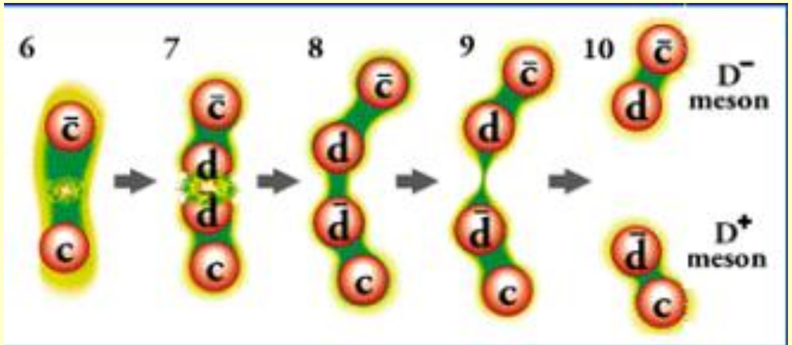
Hard Scattering:
- High p_T, like in Rutherford scattering results.

$\Rightarrow$Hard scattering implies substructure

Most particles Produced at RHIC are "Soft" (Low p_T)

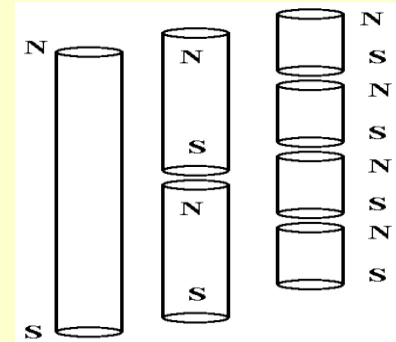


2004 Nobel Prize in Physics: Asymptotic Freedom (1973)



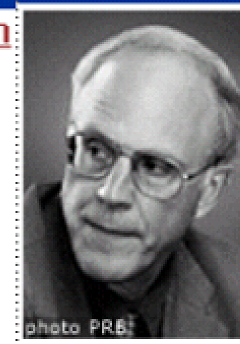
Cannot separate quarks

Cannot separate N and S poles

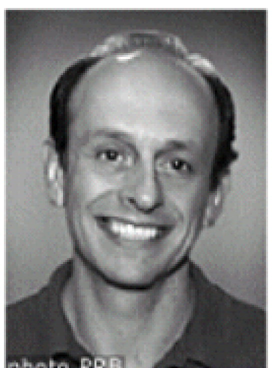


http://www.physicstoday.org/vol-57/iss-10/nobel.html

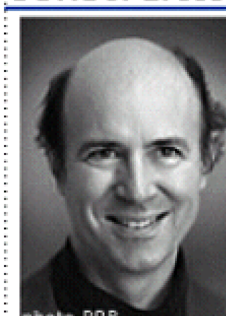
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2004 jointly to



David J. Gross



H. David Politzer



Frank Wilczek

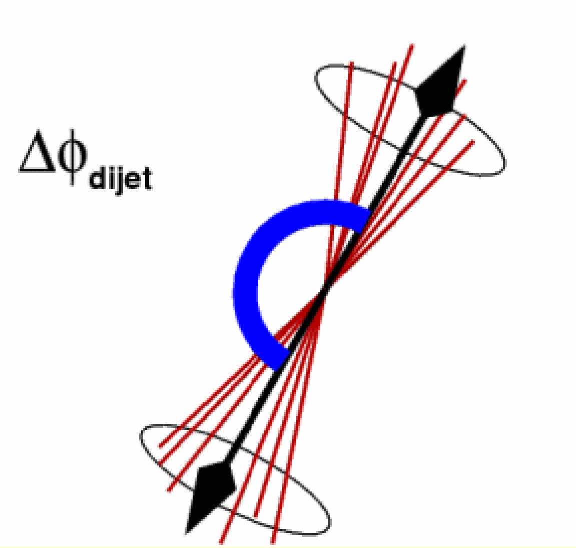
David J. Gross
Kavli Institute for Theoretical Physics, University of California
Santa Barbara, CA, USA

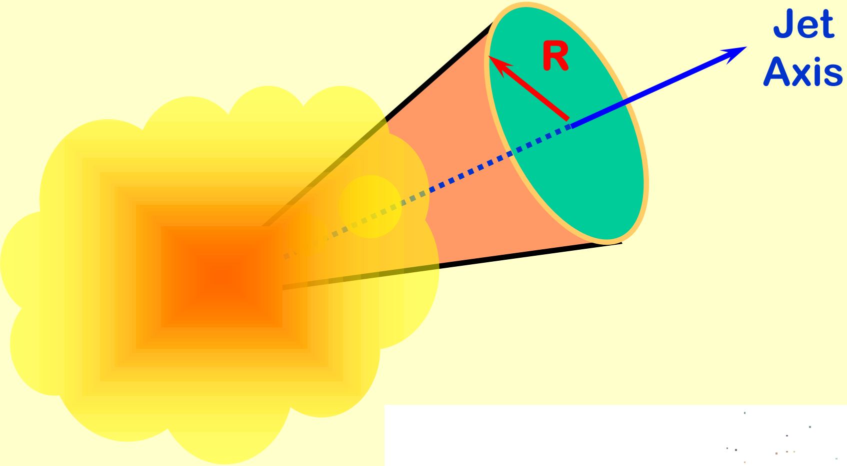
H. David Politzer
California Institute of Technology
Pasadena, CA, USA

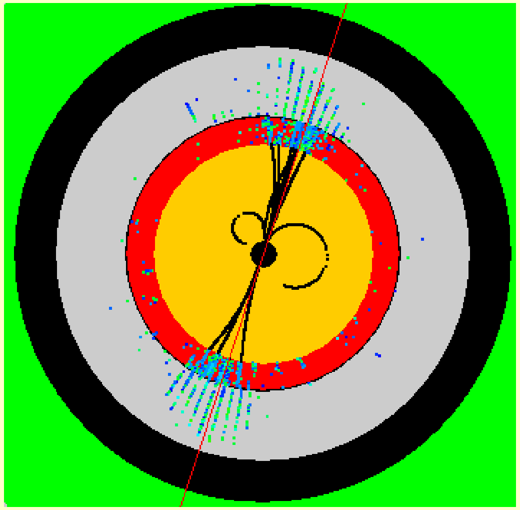
Frank Wilczek
Massachusetts Institute of Technology (MIT)
Cambridge, MA, USA

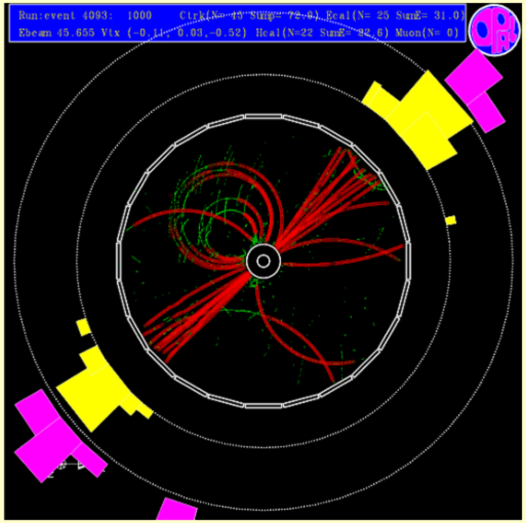
"for the discovery of asymptotic freedom in the theory of the strong interaction"

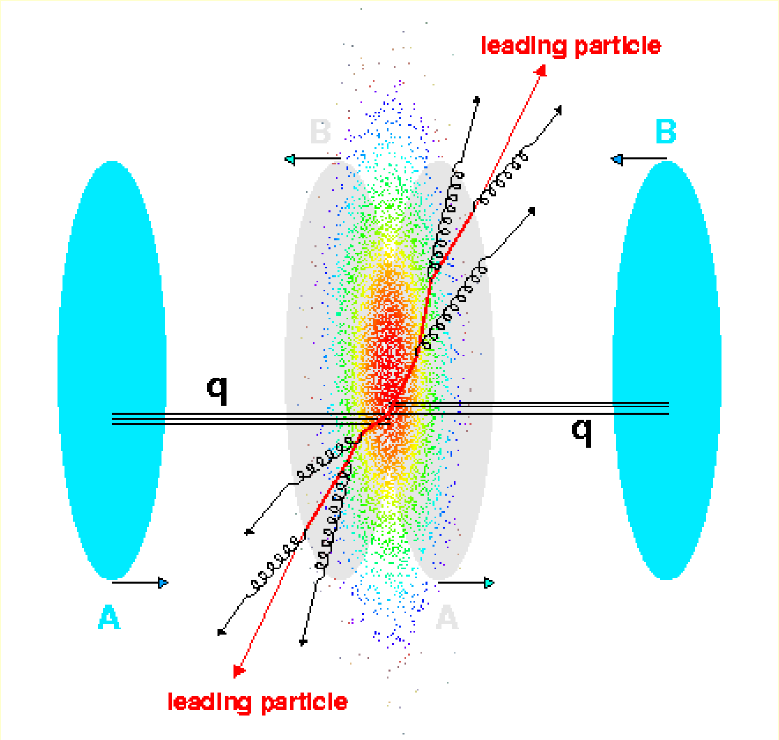
Jets of hadrons produced in high-energy collisions



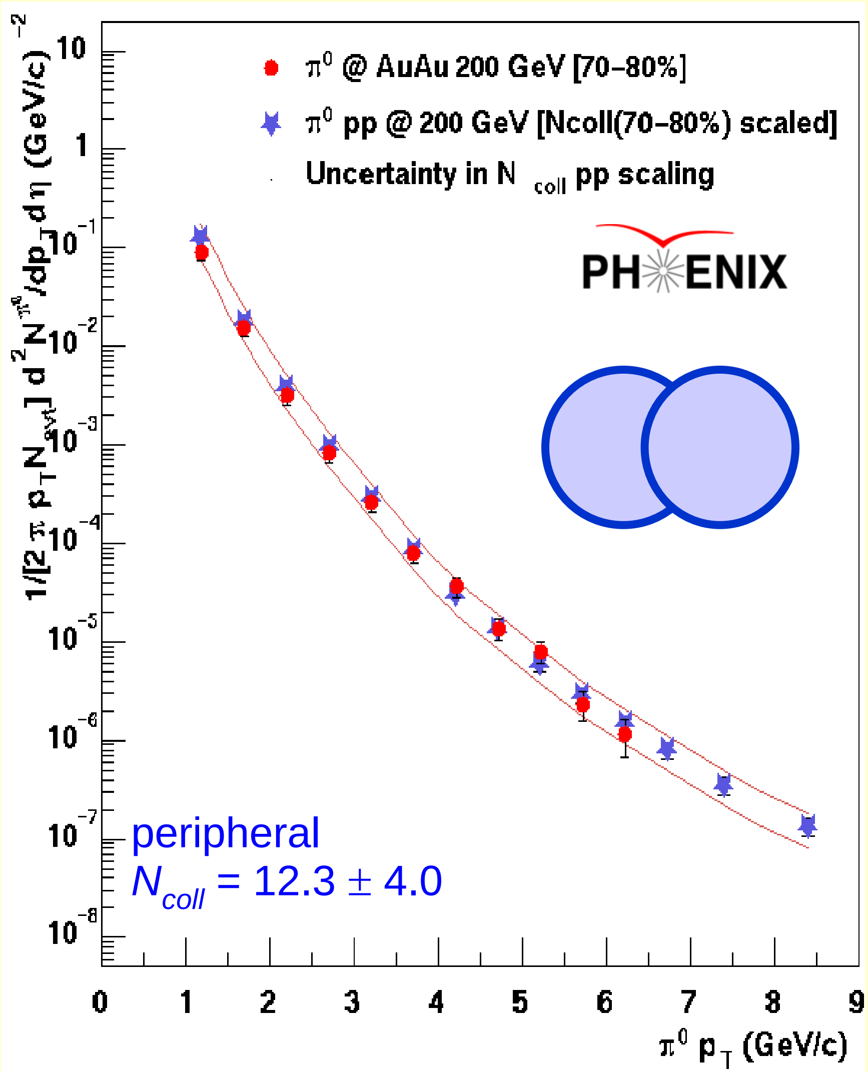


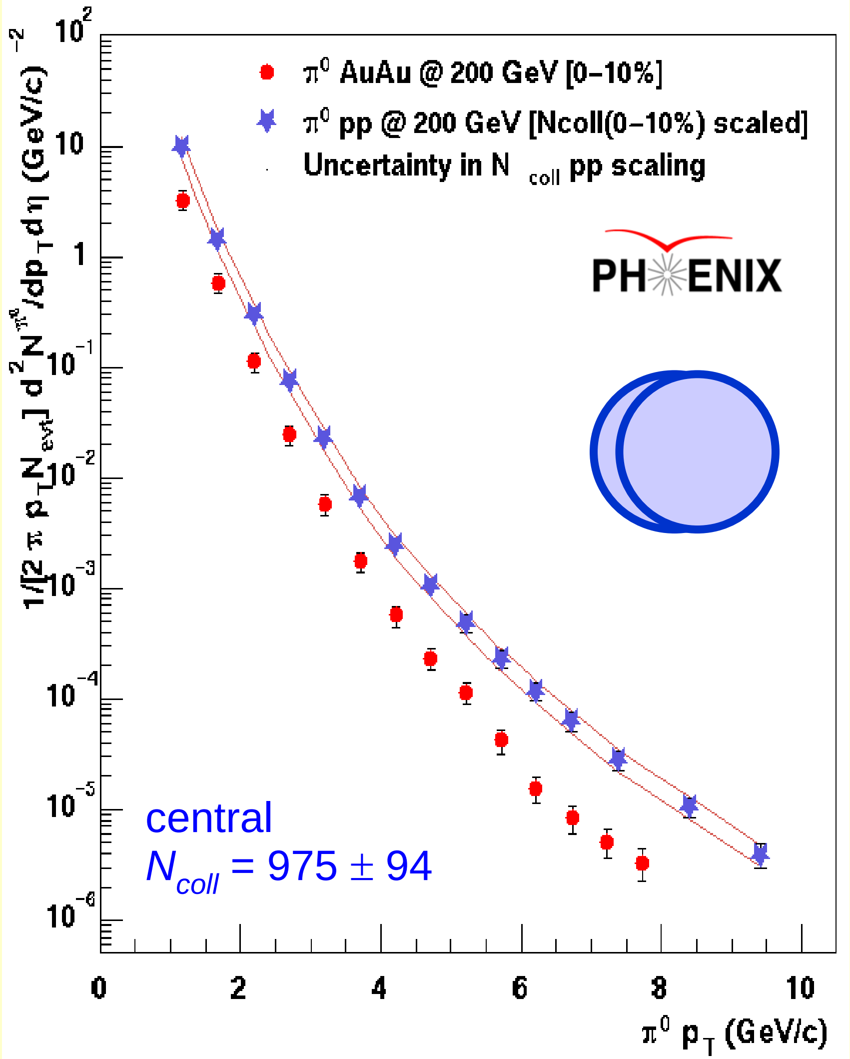




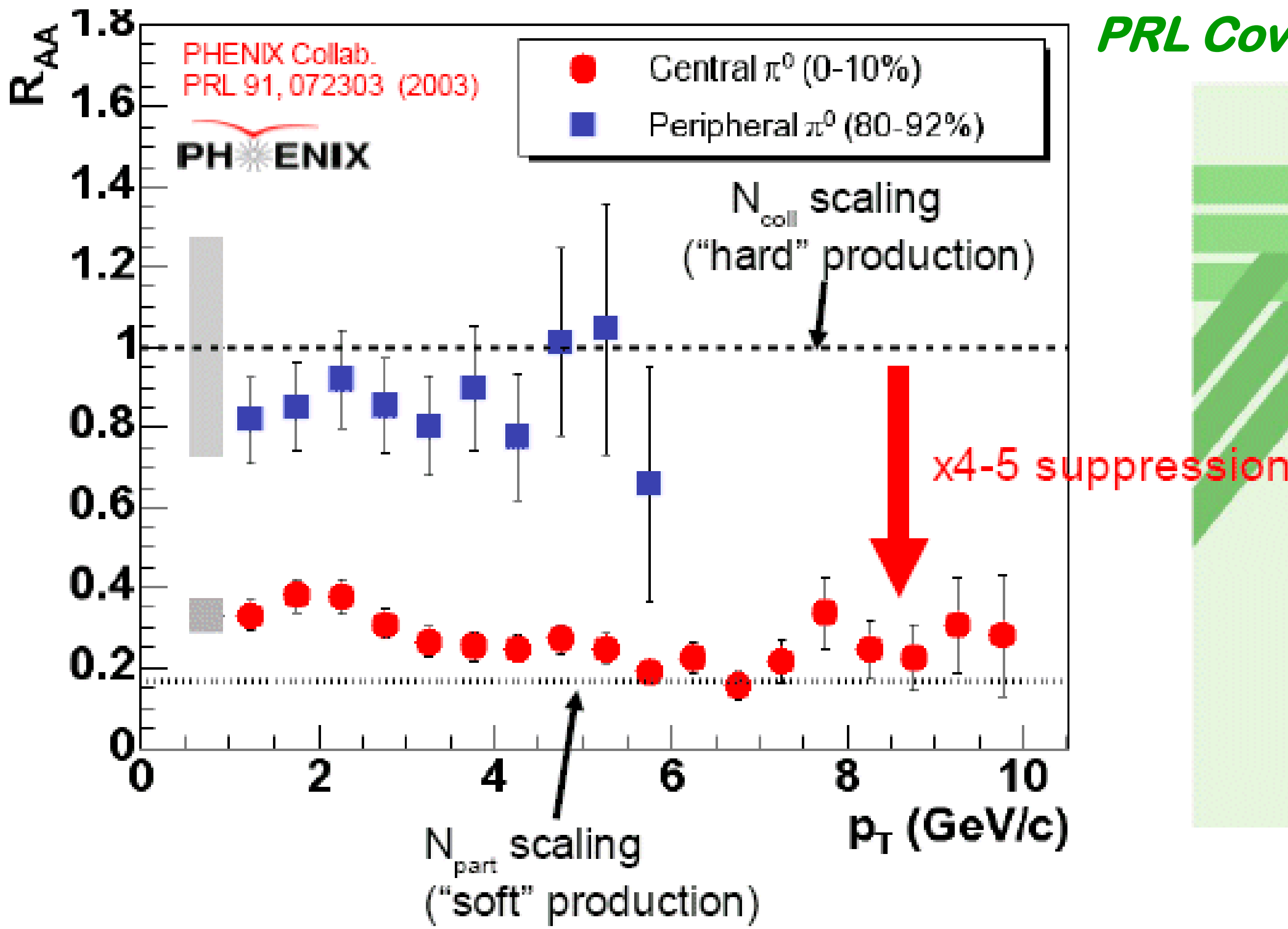


Early Discovery at RHIC: Strong Suppression

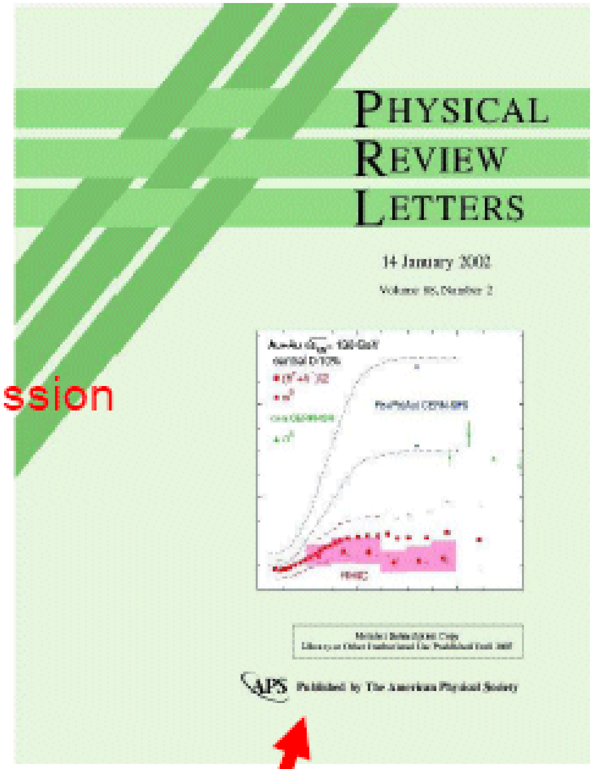




Evidence for a Dense System in Au+Au Collisions



PRL Cover – 14 January 2002



R_{AA} << 1: well below pQCD (collinear factorization) expectations for hard scattering cross-sections

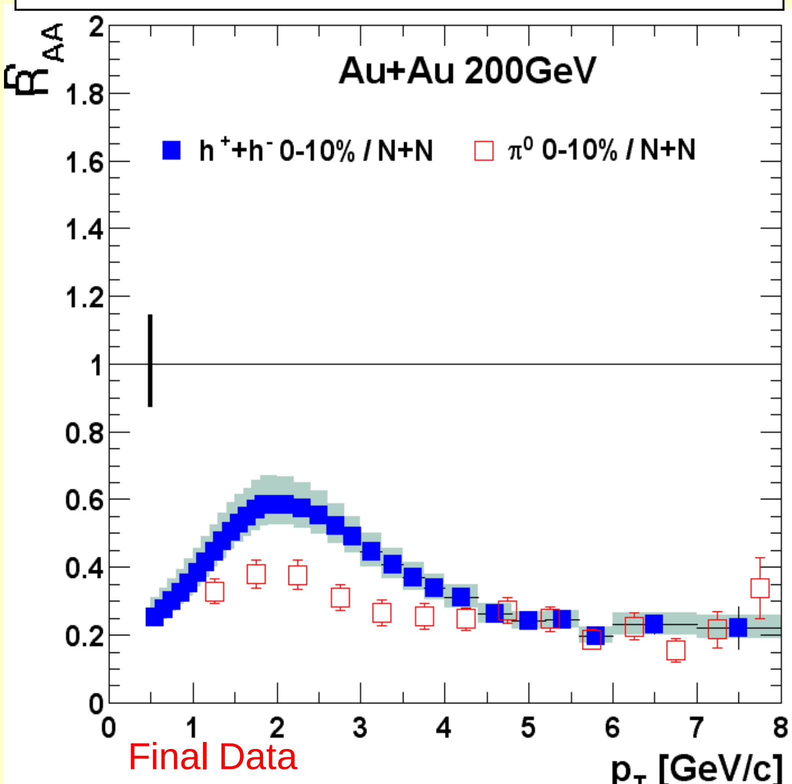
Discovery of high p_T suppression
(one of most significant results @ RHIC so far)

Control Experiment: d + Au (cold nucleus)

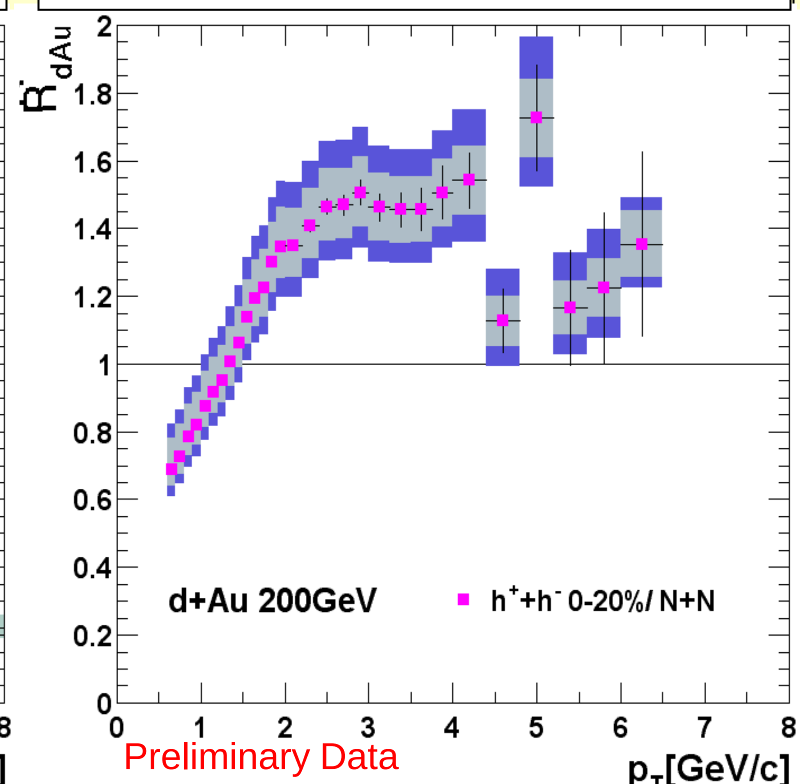
Some theorists suggested that the observed high p_T suppression in Au+Au central events was an initial state effect. If so, then at least some suppression should also be seen in d + Au collisions.

Experimental results (enhancement) falsified the initial-state conjecture.   Conclusion: *<u>Au+Au result is a final-state effect.</u>*

Au + Au Experiment



d + Au Control Experiment



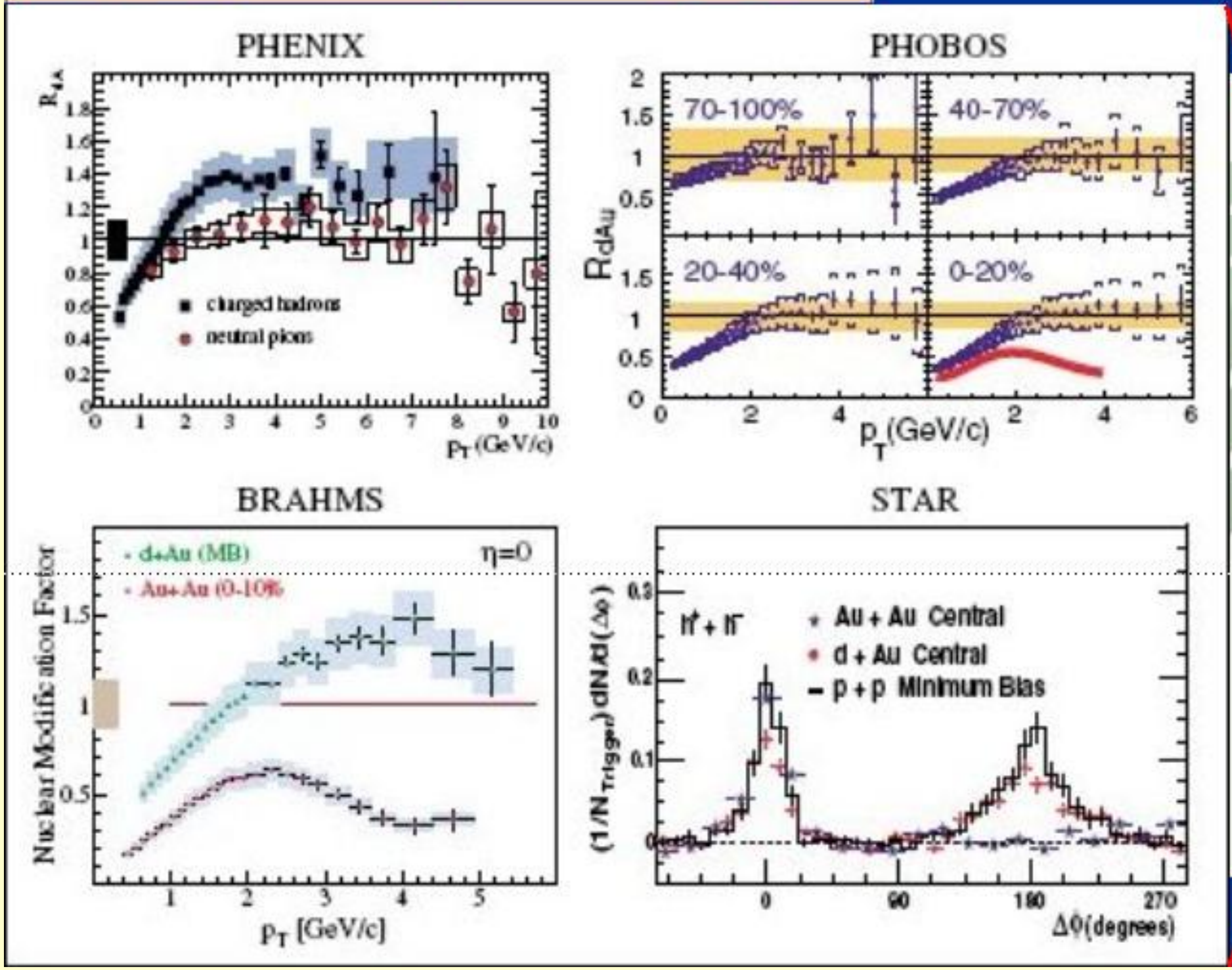
Evidence for a Dense Final State System

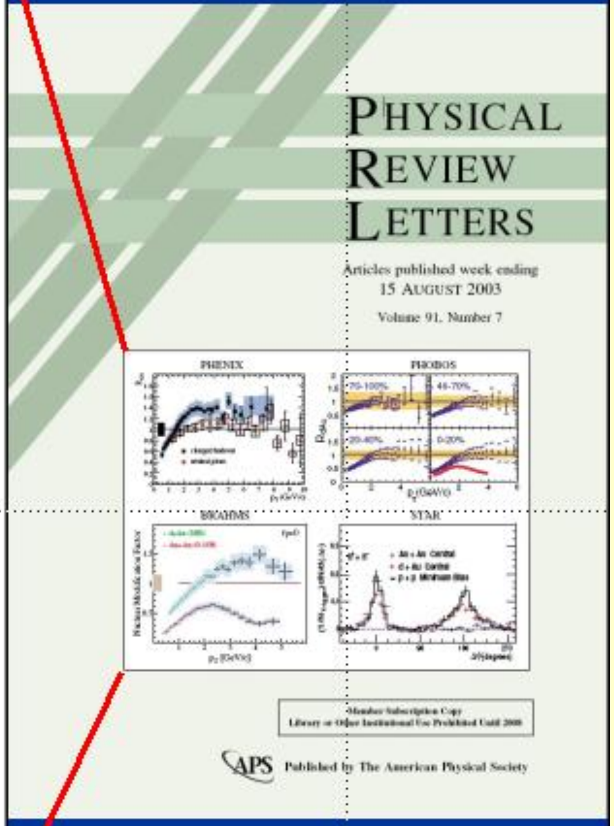
d+Au results from

BRAHMS PHENIX PHOBOS STAR

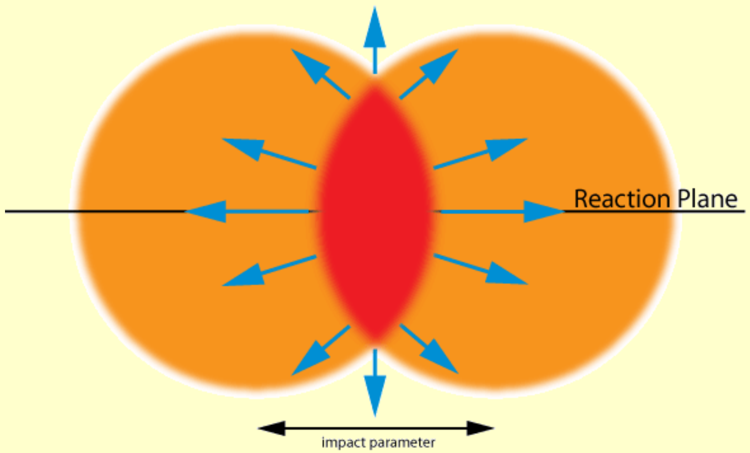
Presented at a BNL "Press Event" 18 June 2003.

PRL Cover 15 August 2003

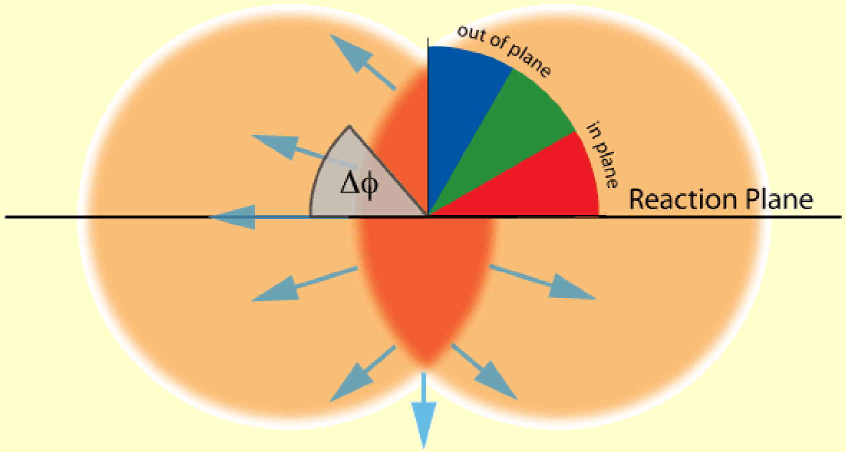


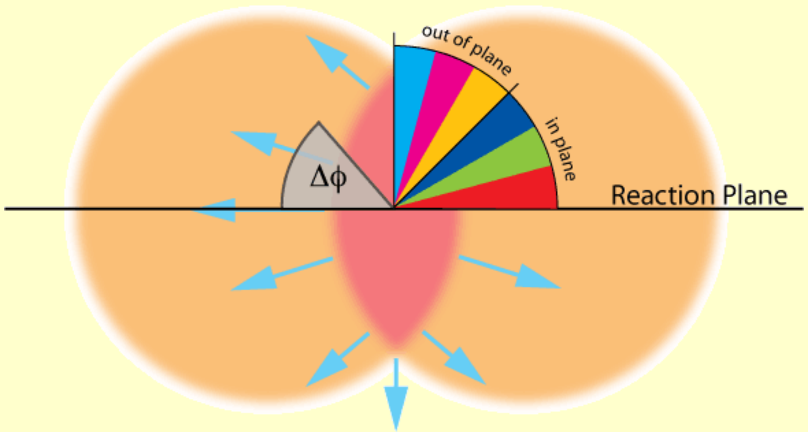


Azimuthal Anisotropy



For semi-central collsision
Initial spatial anisotropy
evolves into
momentum anistropy
but ONLY if strongly coupled!

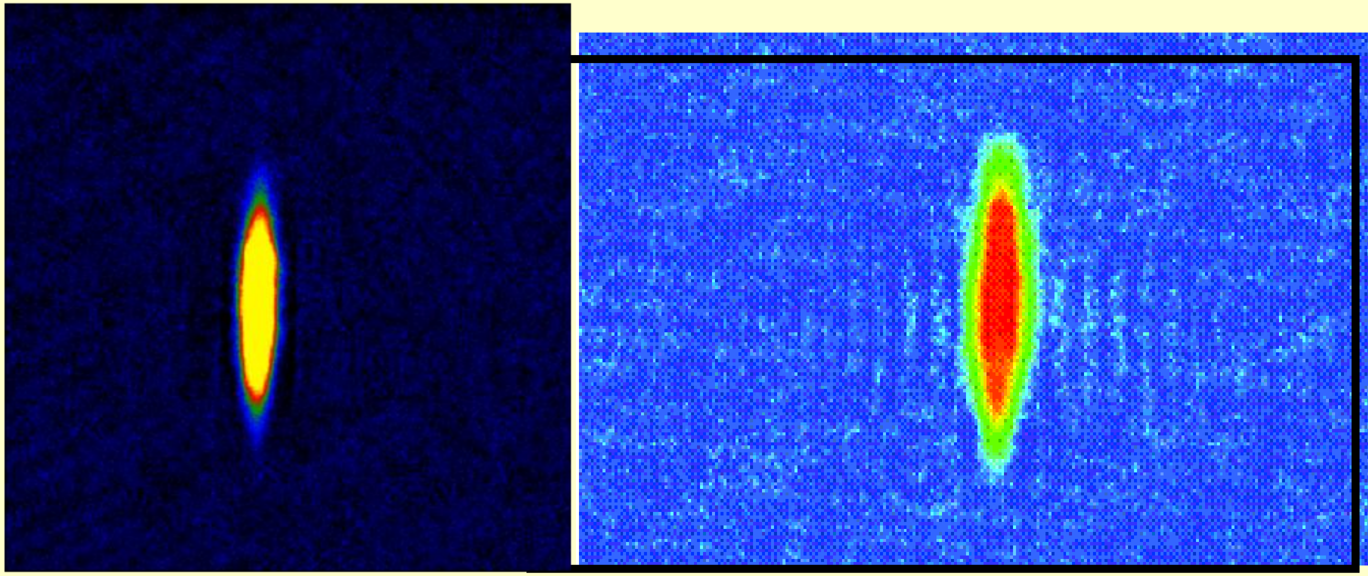


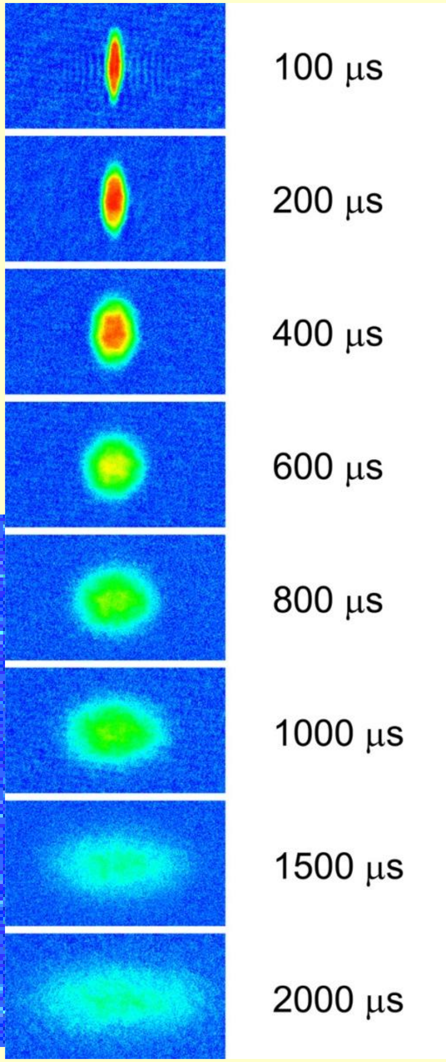


Anisotropic Flow in gases of atoms

Same phenomena observed in gases of strongly interacting atoms. M. Gehm, S.Granade, S. Hemmer, K, O'Hara, J. Thomas. Science 298 2179 (2002)

weakly coupled **strongly coupled**

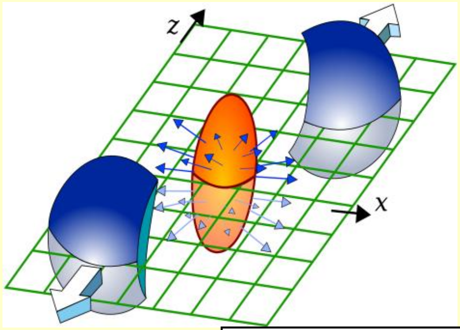




The RHIC fireball behaves like a strongly coupled fluid

Azimuthal Anisotropy -- Elliptic Flow

Strong Initial Pressure Gradient

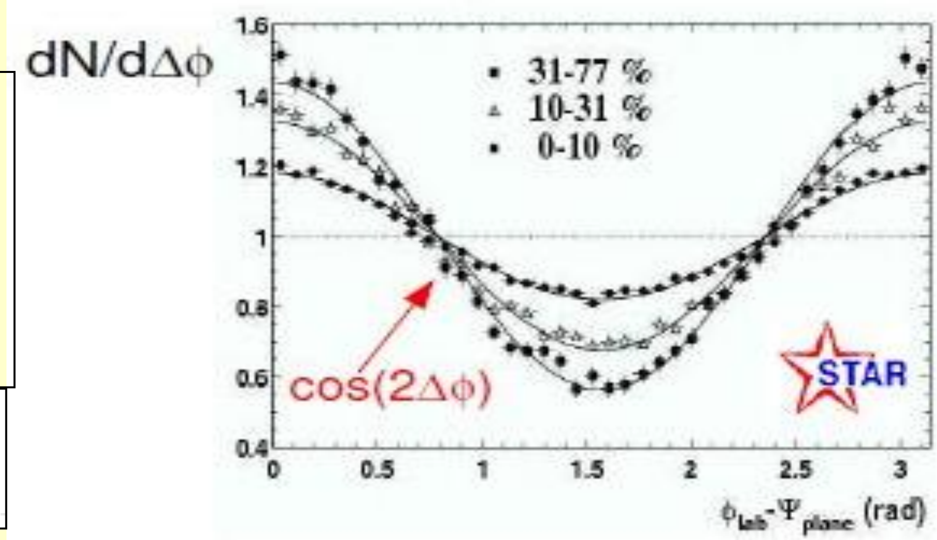


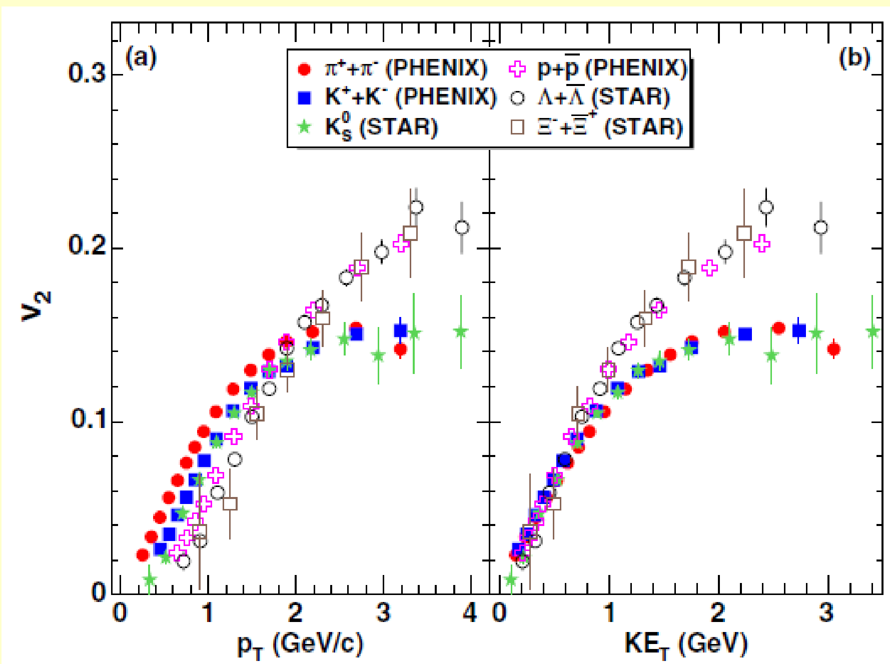
Elliptic Flow

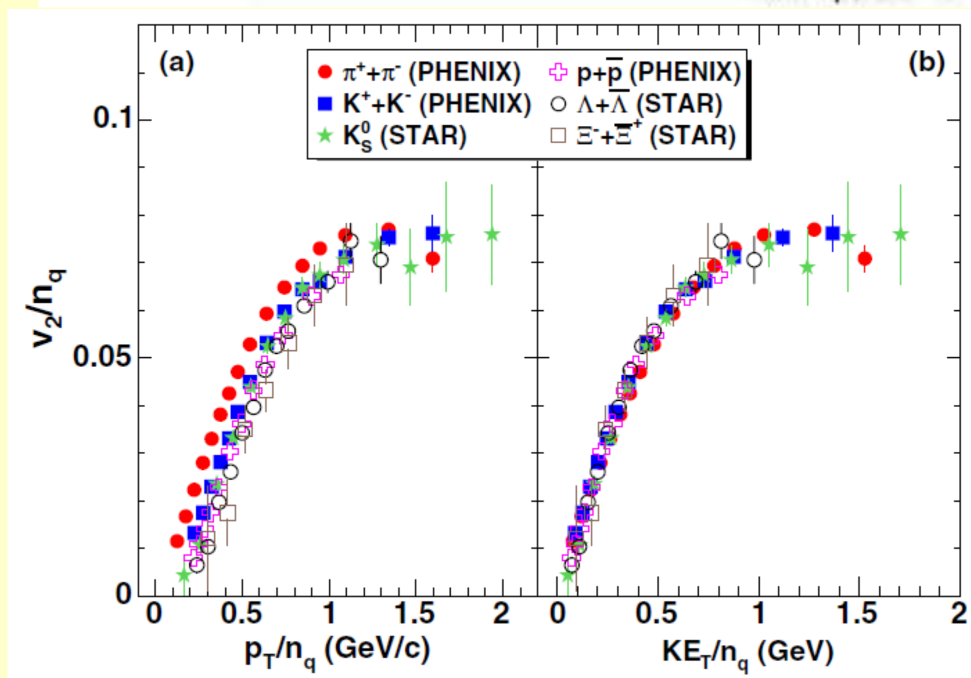
v_2

= 2nd Fourier Coefficient

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi_{RP})$$



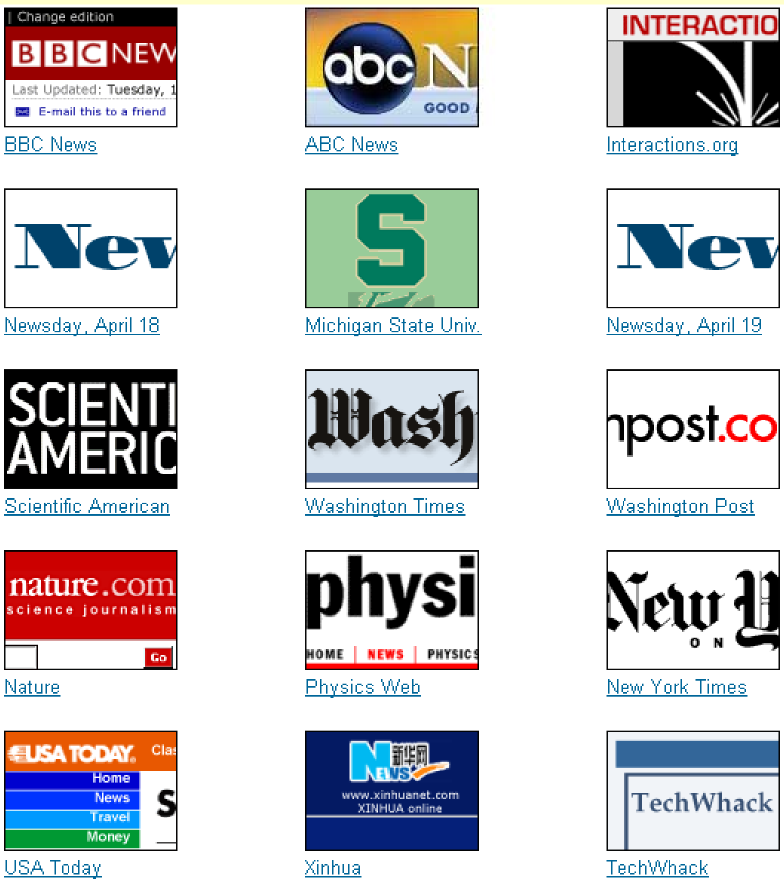


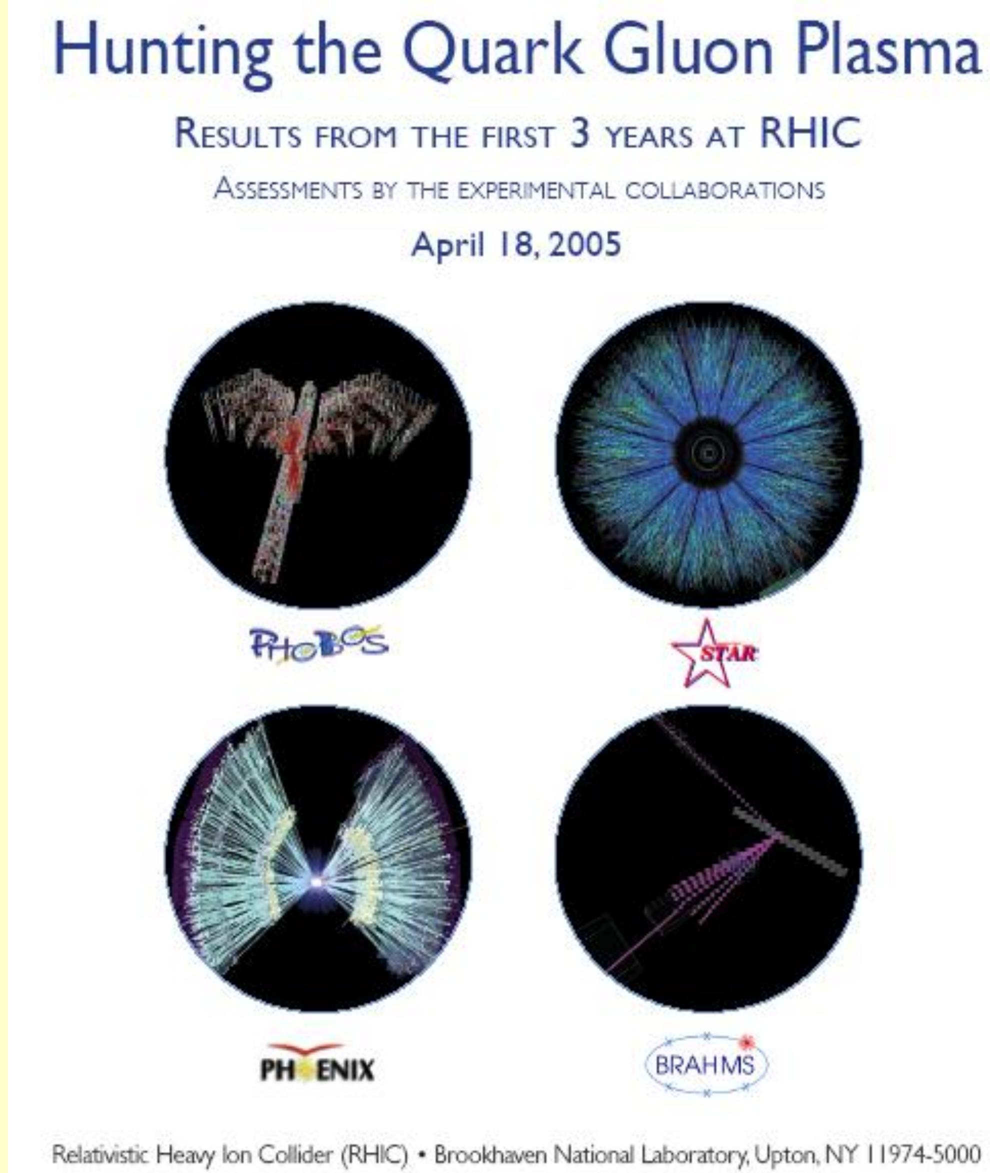


RHIC Scientists Serve Up "Perfect" Liquid

RHIC Press Conference held Monday, April 18, 2005 in Tampa, FL at the April Meeting of the American Physical Society.

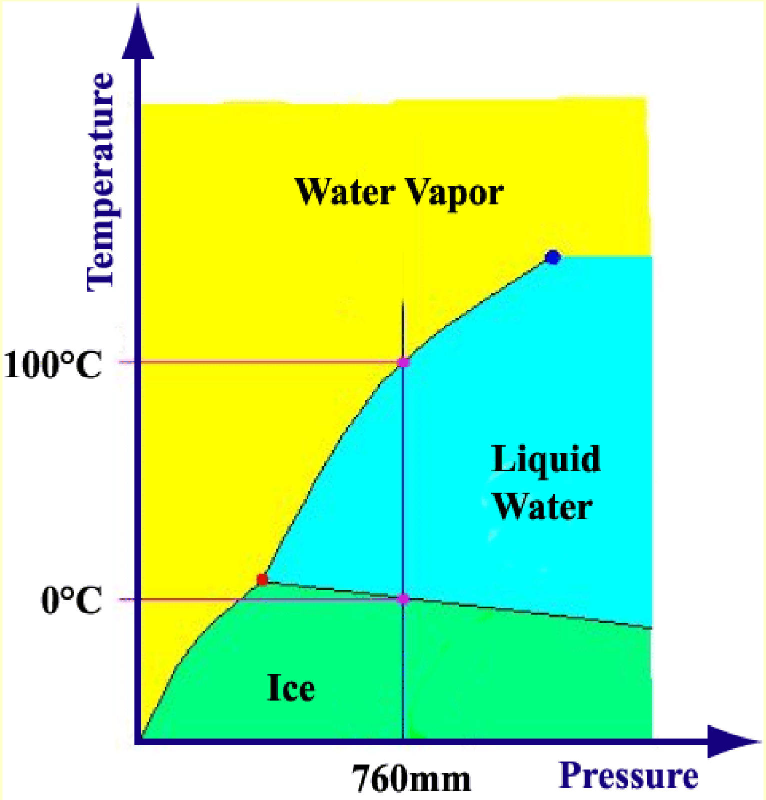
At least 148 news articles worldwide:

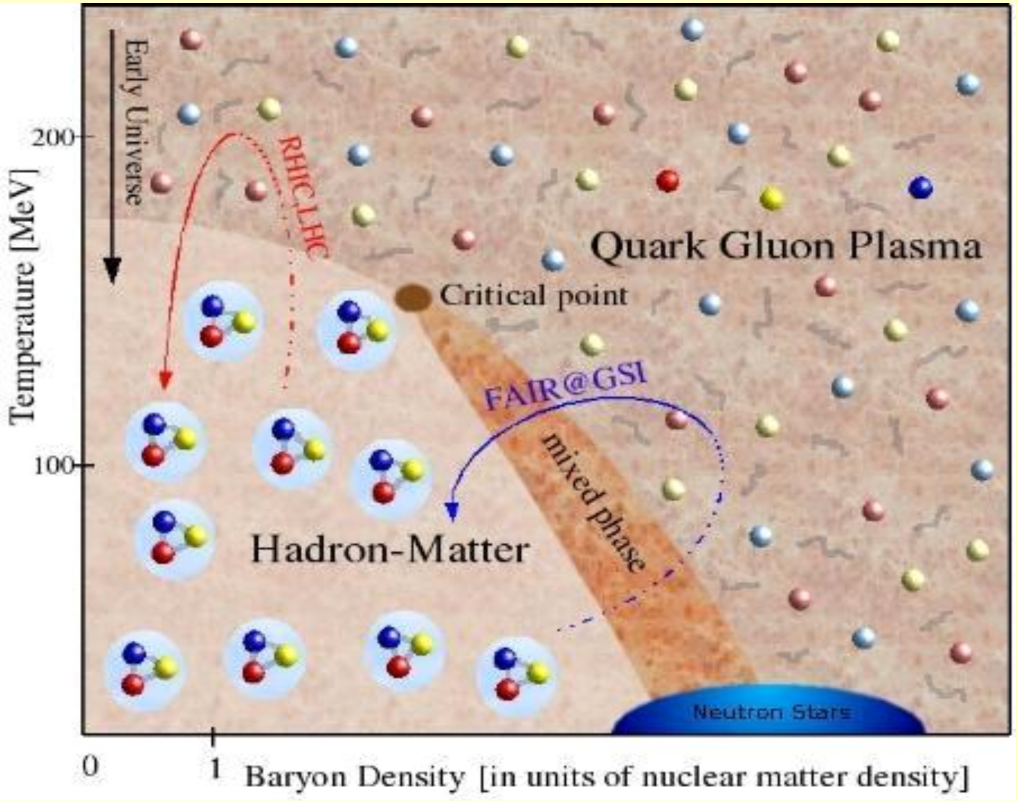




Ice-Liquid Water-Steam and QCD Phase Transitions

- **The colliding nuclei at RHIC energies are expected to melt from bags of protons and neutrons into a collection of quarks and gluons**

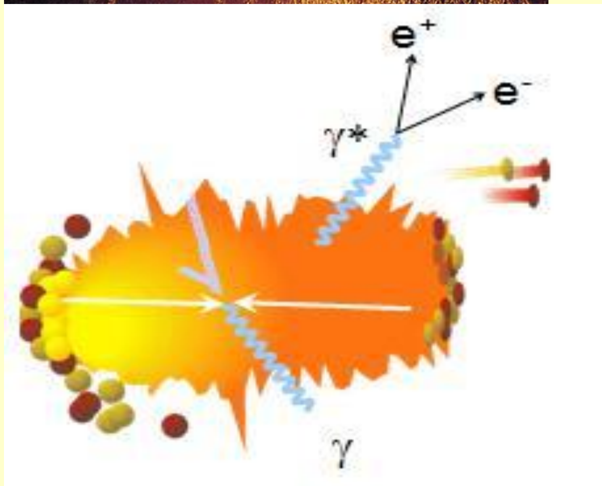




Goal: Measure the initial temperature of matter formed at RHIC

Is T_{init} higher than T_c ~ 170 MeV (~ 1 GeV/fm^3)

Press event at Feb. 2010 APS Meeting in Washington, DC

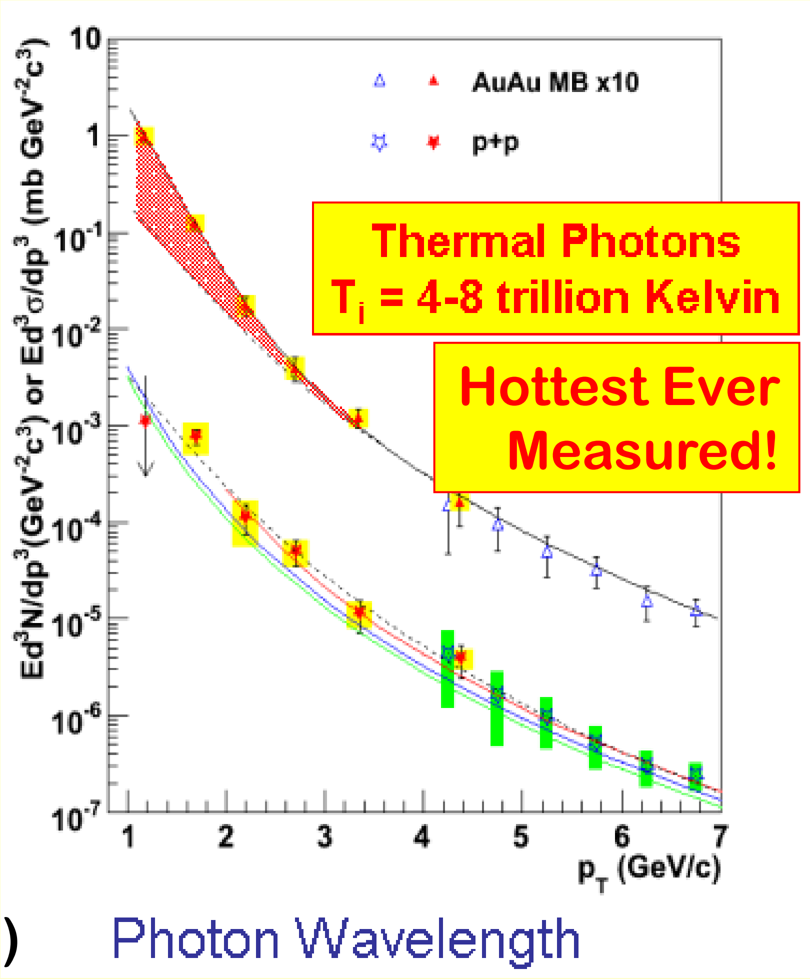


Hot matter emits Thermal radiation

Temperature can be measured from the emission spectrum

PHENIX

PRL 104, 132301(10); PRC 81, 034911(10)



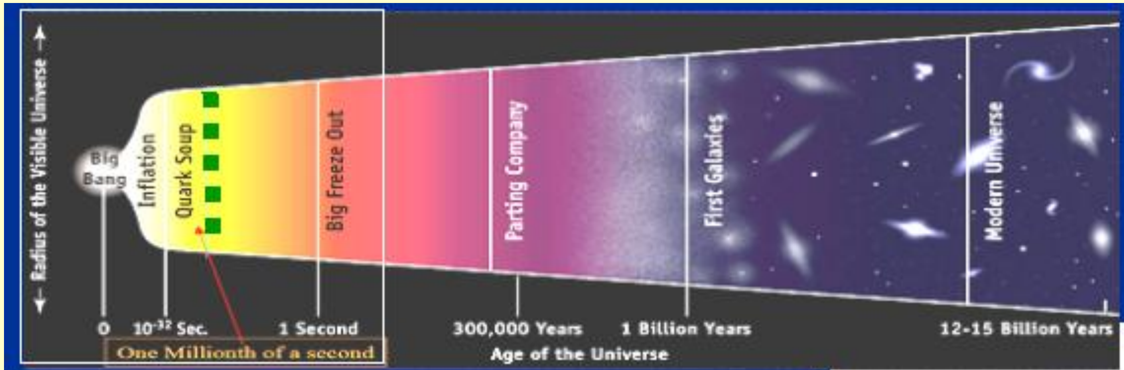
The Hottest Science Experiment on the Planet

In a Long Island lab, gold particles collide to form a subatomic stew far hotter than the sun.

by Calla Cofield

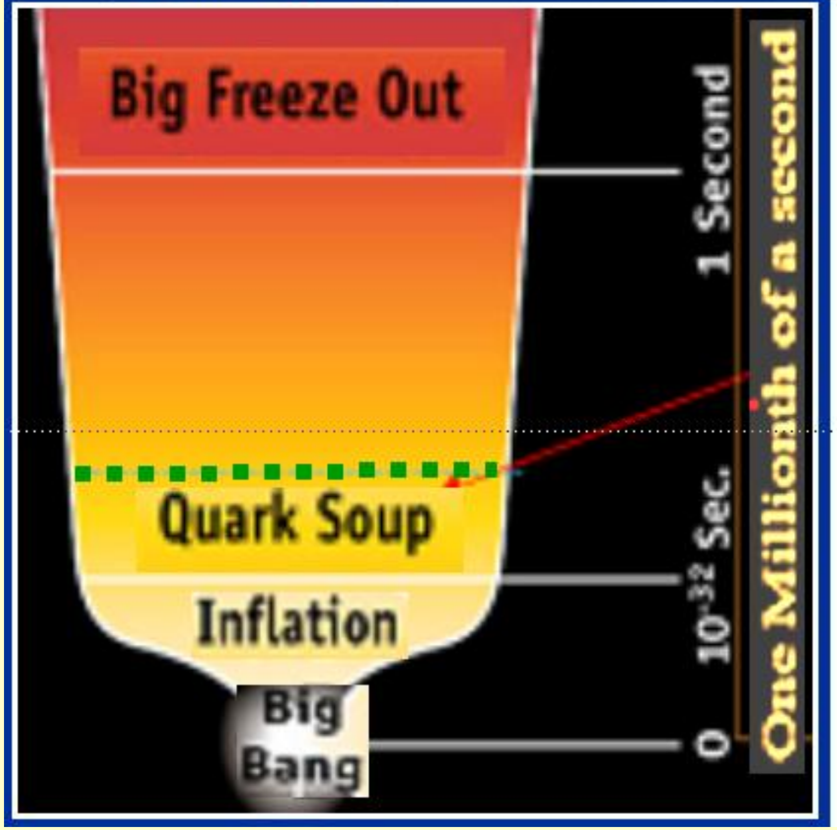
published online February 15, 2010

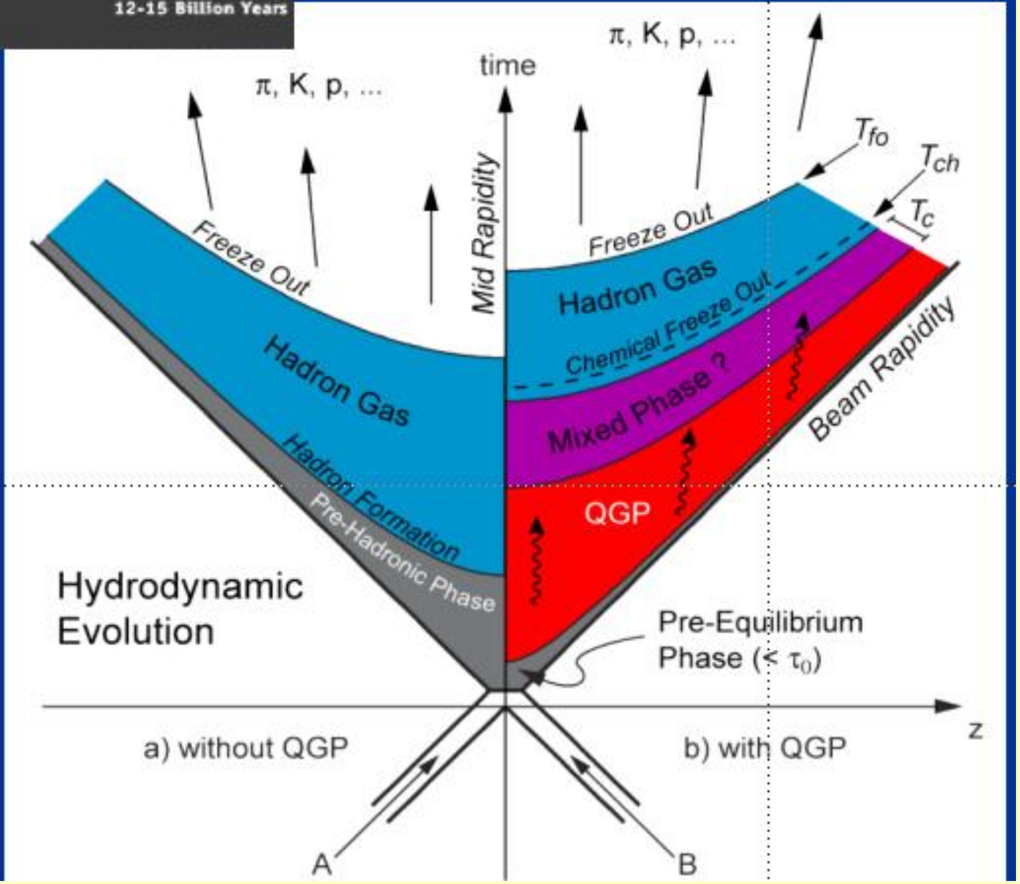
Physics at a Few Millionths of a Second After the Big Bang



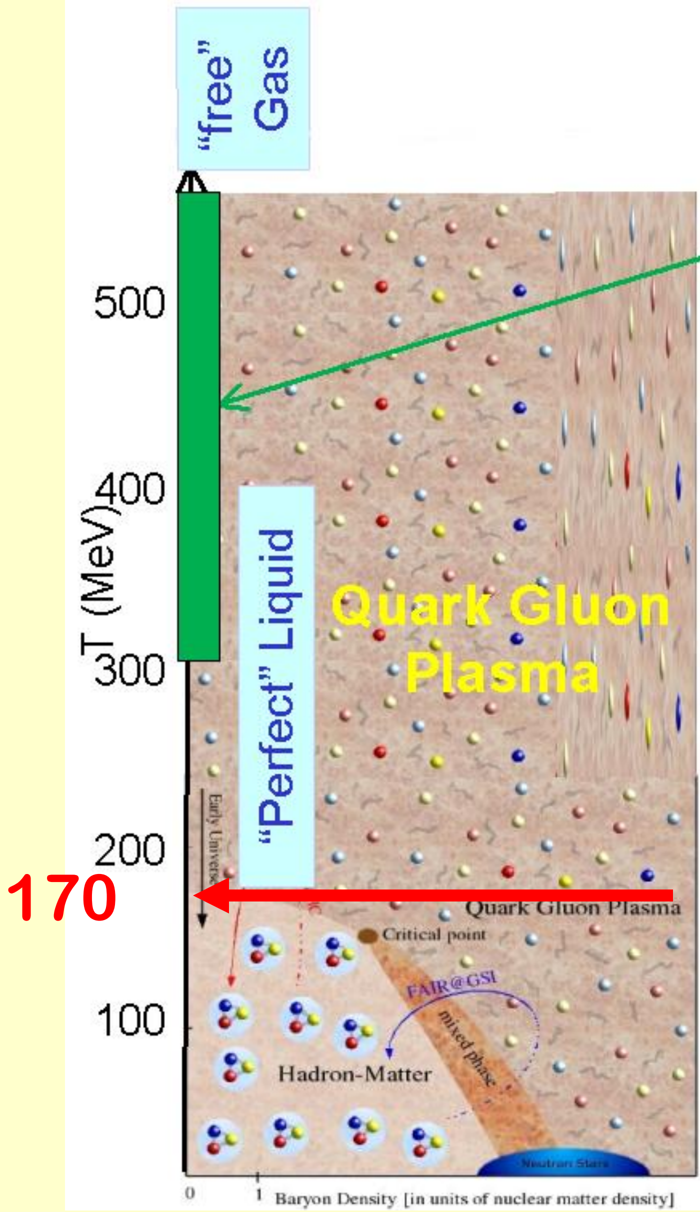
Today is ~14 billion years later.

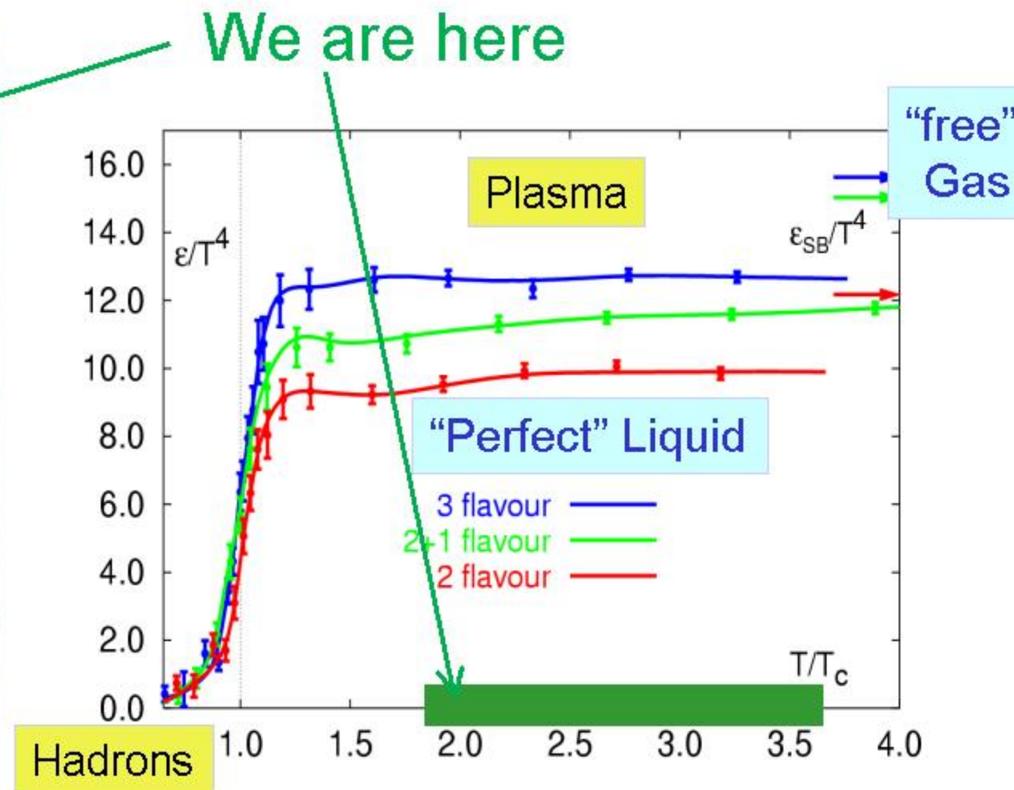
Most particles detected are hadrons after Freeze Out





Where are we on the QGP map?





T_c ~ 170 MeV; ε ~ 1 GeV/fm^3

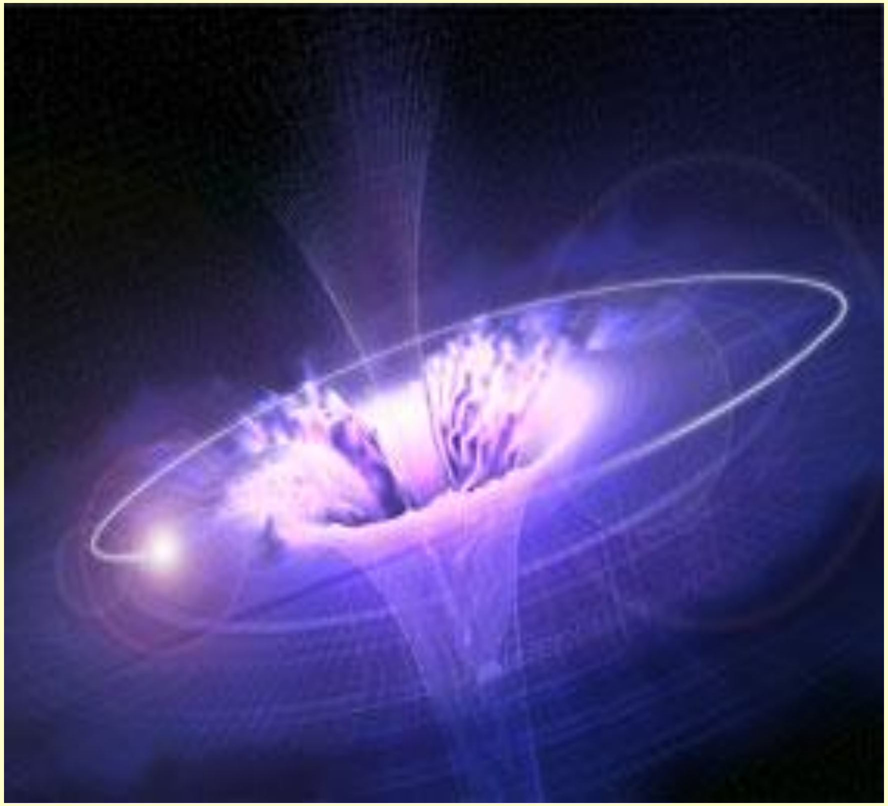
At these temperature, QGP is *"perfect" liquid.*

At higher temperature, it can become *"gas"*

How could string theory be relevant?

The Maldacena duality, known also as AdS/CFT correspondence, has opened a way to study the strong coupling limit using classical gravity where it is difficult even with lattice Quantum Chromodynamics.

It has been postulated that there is a universal lower viscosity bound for all strongly coupled systems, as determined in this dual gravitational system.



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Words to communicate concepts

Brookhaven National Laboratory **Relativistic Heavy Ion Collider**

Understanding
Observation
Experiment
Theory
Light Wave
Photon

The Atom
Hard Sphere Model
Plum Pudding Model
Nuclear Atom
Soft/Hard Scattering
Electron Wave
Wave-Particle Duality
Quantum Mechanics

small, very small
very fast
Mechanics:
Classical
Quantum
Relativistic

The Nucleus
Nucleons:
Proton & Neutron
Radioactive Decay

Particles & Fields
Parton: Quarks and Gluons
Baryons, Hadrons
π Meson (pion)

Leptons
Electron e^- Positron e^+
Muon μ^- μ^+ Tau τ^- τ^+
Neutrinos ν_e ν_μ ν_τ

Strong suppression
Dense final state
Anisotropic Flow
Nearly perfect fluid
Asymptotic Freedom
Phase Transitions
Deconfinement
Early Universe
(Big Bang)

Direct and Virtual Photons
Hottest Temp. Measured